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EXPLORING THE IMPACT OF FUEL DATA ACQUISITION TECHNOLOGY ON THE USMC EXPEDITIONARY ENERGY COMMAND AND CONTROL SYSTEM

by

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September 2016

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13. ABSTRACT (maximum 200 words)

Marine Corps commanders have inadequate tools for energy awareness on the battlefield. The purpose of this study is to explore how vehicle telematics could impact operational reach through improving awareness of fuel stocks from hours to near-real time. The research uses an exploratory sequential mixed methods design to establish how current practices may change with the introduction of telematics. The first-phase qualitative findings suggest that the tactical fuel supply chain is inherently unstable due to information delays and information processing distortion. The second phase tests the hypothesis that telematics has a positive effect on operational reach. This is accomplished through a supply chain simulation that compares the current process against a reengineered solution with telematics. Between the two models, the reengineered supply chain produced the opportunity for higher tempo, more agile combat units, and increased system stability. While these are desirable effects, operational reach was reduced by 7% as fuel was more available to combat units. In addition to fuel-saving initiatives that telematics may inform, there may be long-term benefits that warrant the full integration of fuel telematics throughout the military supply chain

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EXPLORING THE IMPACT OF FUEL DATA ACQUISITION TECHNOLOGY ON THE USMC EXPEDITIONARY ENERGY COMMAND AND CONTROL SYSTEM

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Marine Corps commanders have inadequate tools for energy awareness on the battlefield. The purpose of this study is to explore how vehicle telematics could impact operational reach through improving awareness of fuel stocks from hours to near-real time. The research uses an exploratory sequential mixed methods design to establish how current practices may change with the introduction of telematics. The first-phase qualitative findings suggest that the tactical fuel supply chain is inherently unstable due to information delays and information processing distortion. The second phase tests the hypothesis that telematics has a positive effect on operational reach. This is accomplished through a supply chain simulation that compares the current process against a reengineered solution with telematics. Between the two models, the reengineered supply chain produced the opportunity for higher tempo, more agile combat units, and increased system stability. While these are desirable effects, operational reach was reduced by 7% as fuel was more available to combat units. In addition to fuel-saving initiatives that telematics can inform, there may be long-term benefits that warrant the full integration of fuel telematics throughout the military supply chain.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAEFS	amphibious assault expeditionary fuel system
AIM	automated information module
B1	platoon-level feedback loop
B2	company/battery-level feedback loop
B3	battalion-level feedback loop
C2	command and control
CAN	controller area network
CLC2S	Common Logistics Command and Control System
CLSA	combat logistics support area
COps	current operations section
COTS	commercial off the shelf
DSM	demand-side management
DOS	day of supply
E2C2S	Expeditionary Energy Command and Control System
E2O	Expeditionary Energy Office
ERP	enterprise resource planning
ETL	extract, load, transfer
FARP	forward arming and refueling point
FMU	field management unit
FOps	future operations section
G-3	operations directorate, general’s staff
G-4	logistics directorate, general’s staff
GCSS	Global Combat Service Support
GDN	Global Distribution Network
HERS	helicopter expeditionary refueling system
JCS	Joint Chiefs of Staff
LCE	logistics combat element
LITNO	logistics inter-temporal network optimization
LSR	logistics support request
LSO	logistics support order

LVSR	logistics vehicle system replacement
M970	semi-trailer refueler, 5,000 gallon
MAGTF	Marine Air-Ground Task Force
MDDOC	MAGTF Deployment and Distribution Operations Center
MEU	Marine Expeditionary Unit
MEB	Marine Expeditionary Brigade
MPEM	MAGTF Power and Energy Modeling software
MTVR	medium tactical vehicle replacement
OODA	observe, orient, decide, act
PID	proportional, integral, derivative
S-3	operations directorate, regiment and below
S-4	logistics directorate, regiment and below
SME	subject matter expert
TAFDS	tactical airfield fuel distribution system
TFMS	Total Force Management System
USMC	United States Marine Corps
USN	United States Navy
XML	extensible markup language
XMILE	XML interchange language for systems dynamics

EXECUTIVE SUMMARY

This study explores how delays in resource decision making and tactical supply chains relate to operational reach. Commercial sector success in the use of vehicle fleet telematics suggest that military application of these technologies may improve energy efficiency without sacrificing effectiveness (Henton & Noack, 2015; Robison, 2015). The Marine Corps wants to understand how changing the volume and frequency of resupply may increase operational reach (United States Marine Corps [USMC], 2013). However, fuel distribution data is still a mystery, as the system is unable to track consumption, and human error reduces data quality (Skelding, 2014). The Marine Corps Expeditionary Energy Office manages the development of the Expeditionary Energy Command and Control System (E2C2S), which seeks to provide commanders with the ability to maximize operational reach (Daniel, 2015, p. 1). Understanding synergies gained from feedback loops in the system is important to maturing technology for effective use (J. Caley, personal communication, October 10, 2015).

A. PROBLEM STATEMENT

The problem is that dynamic demands create high stock requirements, which encumber supply and distribution capacity in the Marine Air Ground Task Force (MAGTF). This is a problem because the operational reach of the task force is constrained to the flow of fuel from external sources. Resupply missions create vulnerability to asymmetric threats on ground lines of communication. Marines risk casualties and material losses as they attempt to mitigate energy-based risks to front line missions.

B. RESEARCH QUESTION/HYPOTHESIS

With a lack of understanding of causal factors in fuel consumption, the exploratory phase of the study asked questions that would guide field observations and interviews. Qualitative in nature, the initial research question was open-ended. The sub-questions were more direct to fill gaps in the emergent themes in with demand processing within the inductive, grounded approach.

How is energy performance data used in a tactical environment?

- What are the hardware capabilities and limitations of sensors?
- What are the transmission capabilities and limitations of the control system field management units?
- What manual, analog, and digital information processes are currently used to meter and forecast fuel demand?

The findings of the first phase were the input for data collection in the second phase. The quantitative analysis assumed that telematics would eliminate or reduce delays and distortion in processing demand information throughout the supply chain. The qualitative findings suggested delays are a cause of inefficiency and reduced operational reach. As such, the hypothesis states a directional relationship between telematics and operational reach. The sub-questions are the dynamic hypotheses that are formed by assuming the interaction of inventory coverage and information delays predict settings where stocks will be depleted and disrupt continuous operations. This assumed that fuel stocks are a valid proxy for operational reach as they were observable and measurable.

Data from fuel telematics has a positive effect on the operational reach.

- High information delay and high inventory coverage has no impact on operational reach.
- High information delay and low inventory coverage has a severe impact on operational reach.
- Low information delay and high inventory coverage has no impact on operational reach.
- Low information delay and low inventory coverage has a moderate impact on operational reach.

C. METHODOLOGY

The mixed methods study employed an exploratory sequential design. The output of the qualitative first phase was the input for the quantitative second phase. The qualitative phase collected data from participant observations, interviews, and extant literature on energy performance studies. The analysis led to an As-Is/To-Be conceptual model of the tactical fuel supply chain. The To-Be model applied system dynamics principles to reengineer the demand information processing based on a hypothetical system that would acquire data via telematics, which would make this data available to various levels of the system in near-real time. Classic system dynamics supply chain models informed an experimental design for the quantitative phase (Sterman, 2000).

D. ANALYSIS

Findings from the first phase attributed delays and distortion of supply and demand for dysfunction in the system. The quantitative methods applied a system dynamics modeling software, Stella, to create an experiment that would simulate the As-Is/To-Be supply chains in a controlled environment. The simulation captured the fuel stocks within a Marine Expeditionary Brigade that flowed to an artillery battery over a 30-day period.

Fully integrated telematics may provide *total demand visibility*, which is the ability of a supply chain activity to adjust supply line responses with near-real time data of retail consumption. Whereas supply trains currently distribute demands registered up to 48 hours before, telematics may allow distributions to reduce the delay by a factor of two at each level of the system.

In the experimental design, an artillery battery plays the retail unit. The battery is consumed fuel at the assault rate, 9,600 gallons per day. The MEB provided fuel to the battalion, and the battalion provided fuel to the battery. Supply trains that delivered fuel 24-hours after receiving orders connected the fuel stocks. On the fifth day of the simulation, the demand of the battery fell to and remained at the sustained rate, 9,000 gallons.

For the As-Is system, the change in demand threw the battery stock into oscillation indefinitely. The oscillations amplified by the same ratio in both systems. The difference is that the To-Be design is able to get ahead of dysfunction caused by the delays. When the change in demand occurs, each supply node changes its orders by the same fractional rate the orders changed at the retail level. The To-Be system absorbed the perturbation over a week and reached 95% equilibrium. Observations of the MEB inventory showed that operational reach between the two systems oscillated, but at 30 days, the As-Is MEB stock was 7% greater than the To-Be system. The results did not support the hypothesis as formulated.

E. RECOMMENDATIONS

The E2C2S functionality will benefit from full integration of telematics in tactical vehicles. The current tactical supply chain operates resource decisions with bounded rationality, as it does not account for the delays that are latent in the system. The data on fuel performance engineered with a bottom-up approach with the measurements in gallons may limit the distortions caused by translations into days of supply or other abstractions when it is propagated forward in the system.

Demand data acquired via telematics did not improve operational reach from an endurance perspective at the MEB-level. With fully integrated inventory adjustments from the platoon level at each resource decision point, the supply chain behaved with greater resilience. The increased availability of fuel at the platoon level created opportunities to lower inventory coverage and distribution maxima. This suggests that the logistics footprint was reducible while utilization rates of distribution assets were increasable. Optimizing these factors may lead to an increase in the operational reach of the unit from a time and space perspective.

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I. INTRODUCTION

A. BACKGROUND

1. Expeditionary Energy Strategy

The energy requirements of expeditionary units have been on a significant rise since the introduction of survivability and information technologies on the battlefield in the early 2000s (United States Marine Corps [USMC], 2010). The energy requirements are primarily supported through converting liquid fuels via combustion engines. Fuel demands are forecasted using point estimates that are not controlled for operating or environmental conditions, which is perceived to have a dynamic effect on liquid fuel supply chains in a tactical environment. As a second-order effect of this phenomenon, the logistics footprint of expeditionary units has increased to accommodate the expanded fuel operations.

In 2006, the Marines were directed to "commit to… the development of sensor and communication systems to enable operational commanders to manage fuel allocation and re-supply in real-time during combat operations" (United States Navy [USN], 2006, p. 3). The directive was a response to experiences commanders shared about fuel constrained operations and dysfunctional tactical supply chains (Chiarotti, 2007). The USMC (2010) expeditionary energy strategy intended "to change the way the Marine Corps employs energy resources to increase combat effectiveness and reduce our need for logistics support ashore" (p. 13).

2. Expeditionary Energy Command and Control System

The Expeditionary Energy Command and Control System (E2C2S) acquisition program was initiated in 2013 with a purpose to "integrate commercial and government energy measurement devices on equipment that consumes, distributes, produces, or stores fuel and/or power, and then feed performance information to commanders" (Daniel, 2015, p. 1). At this stage of the program, the Expeditionary Energy Office (E2O) has sponsored several studies that contributed to the body of knowledge that suggest a positive relationship between commander's access to energy performance data and their

respective unit's operational reach in the Marine Air Ground Task Force (MAGTF) (Daniel, 2015). Operational reach is defined as "a boundary of the campaign that is operationally feasible from the logistics point of view… measured in two dimensions: time and space" (Kress, 2002, p. 594).

3. Data Acquisition Technology Implementation

A human factors study found gaps in information processes and suggested interventions that may reduce inefficient energy practices (Salem & Gallenson, 2014). The E2O selected a commercial-off-the-shelf (COTS) wireless fuel metering technology to test its ability to perform data acquisition of fuel performance from vehicles in a tactical environment. The tests raised several questions about how the newly acquired technology may impact operational reach.

B. PROBLEM

1. Problem Statement

Dynamic demands in ground fuel requirements result in high stock requirements for sustained tactical operations in the Marine Corps. The bulk fuel footprint encumbered the organic lift and storage capacity of the MAGTF operating in Iraq and Afghanistan to a point where external resupply continuously increased. This is a problem because the operational reach of the task force is constrained to the external resupply capacity. These resupply missions create a vulnerability to asymmetric threats on ground lines of communication between forward operating bases and their supply nodes. If the high dependency of sustainment via this mode of resupply is not addressed, the Marines will continue to risk casualties and material losses during resupply as they attempt to mitigate energy-based risks to front line missions.

2. Purpose Statement

The purpose of this study is to explore fuel data acquisition technologies and test their impact on dynamic fuel demands through a time series analysis of tactical fuel supply chain simulations (Sterman, 2000; Savage, 2003, pp. 182, 305–307). The simulation focuses on a Marine Expeditionary Brigade (MEB) and its fuel supply chain

down to the platoon level. This research contributes to the body of military science by bridging with the field of systems dynamics to provide insights on factors that drive operational reach and supply chain stability in a tactical environment. The results of this research may inform acquisition decisions and operating concepts of military organizations.

C. RESEARCH QUESTIONS AND HYPOTHESES

With a lack of understanding of causal factors in fuel consumption, the exploratory phase of the study asked questions that would guide field observations and interviews. Qualitative in nature, the initial research question was open-ended. The sub-questions were more direct to fill gaps in the emergent themes in with demand processing within the inductive, grounded approach.

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D. METHODOLOGY

1. Mixed Methods

Mixed methods research designs combine and integrate qualitative and quantitative methods of research (Creswell, 2014). The approach uses a technique of triangulation of findings between the two methods as a means mitigating bias of a single approach. This study used an exploratory sequential design; the qualitative phase outputs were inputs to the quantitative portion. The outcome of the study provides "an understanding of participant views within the context of an experimental intervention" (Creswell, 2014, p. 231).

2. Exploratory Sequential Design

The exploratory sequential design separated the study into two phases. The qualitative phase collected data for analysis that built into the quantitative phase (Miles & Huberman, 2014). The experimental intervention examined in the participant observation used resource decision tools that introduced data created by fuel sensor devices through a prototype telematics data acquisition architecture. The quantitative phase of data collection and analysis was designed to test dynamic hypotheses predicting the impact of the telematics may have on the operational reach of Marine Corps units in a tactical environment.

a. Qualitative Phase

The qualitative phase of the study sought to answers to the research questions. The collection of data was mixed between a review of extant literature, participant observation, and semi-structured interviews of participants. Analysis used an inductive, grounded approach (Strauss & Corbin, 1990). The findings were extrapolated to inform

modeling of current (As-Is) and possible future (To-Be) fuel supply chain that was the basis for data collection and analysis in the quantitative phase (Creswell, 2014).

b. Quantitative Phase

The quantitative phase was designed to test the hypotheses through modeling a case of supply chain management into an experimental design. The design was synthesized into a computer simulation. The experimental data was analyzed using time series analysis for stock behaviors and a sensitivity analysis to measure the impact of information delays on supply chain stability. The findings were used to inform the conclusions of the study.

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II. LITERATURE REVIEW

The literature review uses a systems thinking view to discuss related bodies of knowledge that can inform the research question of how fuel telemetry may have a positive effect on operational reach through increased energy awareness. Systems thinking is a branch of science developed "to make the full patterns clearer, and to help us see how to change them effectively" (Senge, 2006, p. 216). Concepts that drive this study will come from fields of systems dynamics, mathematical optimization, theories of human cognition, and studies published by defense and academia focused on managing demand side energy requirements of operating motor vehicles. The review focuses on the design, structure, and behavior of systems and begins with a discussion of stocks, flows, and feedback loops. Next, operational research techniques for planning optimized fuel systems are reviewed with a focus on the inherent gap between assessed stocks, estimated stocks, and actual stocks. Then, a review of existing studies elucidates the need for an experimental design to explore how automating vehicle telematics may minimize the distortion between perception and reality of fuel performance. The chapter ends with a comparative review of Marine Corps doctrine and its connection to fundamental fields of information sciences: control and information theory.

A. SYSTEMS THINKING

1. Systems Dynamics

Reductionist thinking approaches problems by deconstructing a problem down into the smallest components and deducing how changes in that component impact the overall system (Capra, 1996). Proponents of systems thinking argue that reductionist thinking can lead to an over-simplification of a system, which may lead to a limited understanding of the long-term effects of changing a system component on the system as a whole (Capra, 1996; Sterman, 2000; Senge, 2006; Meadows, 2008). The argument associates reductionists with a mechanistic worldview. Proponents question the utility of mechanistic and advocate for systems thinking worldviews (Capra, 1996, p. 27). Systems thinking approaches problems by viewing the world as interconnected systems, best

examined holistically instead of in isolated parts. However, the examiner of a problem must remain focused on solving the problem, not perfectly modeling the behavior of an entire system (Sterman, 2000, pp. 89–93). So, there must be a balance between being too simplified and too complex in order to produce conclusions and recommendations that are useful, accurate, and reliable (Sterman, 2000, 79).

Systems dynamics takes on this challenge with a methodology that assumes a cyclic tendency that persists as a result of balancing flows of input and outputs of system processes. The relationships in a system are formed between causal links that make up the feedback loops within the system. The rate of change in causal links may differ throughout a system. Where there is a significant difference between an inflow and an outflow, a stock emerges. The behavior of stocks in a system reveals the resilience a system. Resilience is a systems ability to absorb perturbations that change flows connected to a stock, which is measured by observing the variation in the stock's level over time (Sterman, 2000).

The complexity of a system rests in the causal factors that effect the flow rates coming in and out of a process. Rates that possess more states characterize complex systems, and more variety is required in feedback mechnisms to regulate the complex system (Shannon, 1948; Ashby, 1956; Beers, 1984; Boyd, 1986). The structure of a complex system may include the combination of intermediate stocks that are governed by competing feedback loops, which creates non-linear behavior in systems (Capra, 1996; Sterman, 2000; Senge, 2006; Meadows, 2008). A technique for understanding complex systems involves observing stock behavior for trends that emerge over time. Systems dynamicists have used qualitative approaches to synthesize trends in behavior into categories or archetypes to faciliate diagnostics (Senge, 2006, pp. 6497–6653).

One of many challenges in systems dynamics is to model the endogenous and exogenous causal factors in a way that reliably accounts for system behavior while accurately portraying the system structure (Sterman, 2000). If this is achieved, then the model can serve as an economic way to test how changes in parameters or structure can impact the performance of stocks over time. The efficacy of this kind of experimentation

is in challenging proposed interventions and discovering counterintuitive or counterproductive effects they may have beyond the immediate future.

The field of systems dynamics offers several examples of system behaviors or trends that can inform the E2C2S system development. The focus of this research is how fuel telematics may impact the fuel supply chain in a tactical enviornment. The specific issues likely to influence system performance are unforeseen demand, unexpected shortfall in stocks, and an uncontrollable growth in consumption that all undermine the operational reach of commanders (Chiarotti 2007). A basic supply chain involves moving units of production, wholesale, distribution, and retail stocks. The stocks leave the system once the retail units flows to a consumer. A simple supply chain would have a uniform flow rate in one direction. The chain would be in equilibrium when inflows, outflows, and stocks remain constant over time. While this is not case in the tactical fuel system, the behavior is desirable as a system in equilibrium is predictable. When uncertainty is introduced, poor management decisions can lead to inefficient supply chains.

The Beer Distribution Game provides a classic example of a supply chain made unstable my management decisions (Sterman, 2000, pp. 684–698). The game shows how feedback delays cause ocillations in supply chains and how human cognition has a tendency to focus only on the immediate state of stocks (Sterman, 2000, p. 694). This focus fails to account for the delays of orders and shipments further up the supply chain. The management decision effects resonate through the system and create unanticipated surpluses and backorders in response to a small change in demand from the consumer. Sterman (2000) accounts for the dynamics in the causal diagram (see Figure 1), which displays the positive relationships between delivery delay, the desired supply line, and indicated orders.

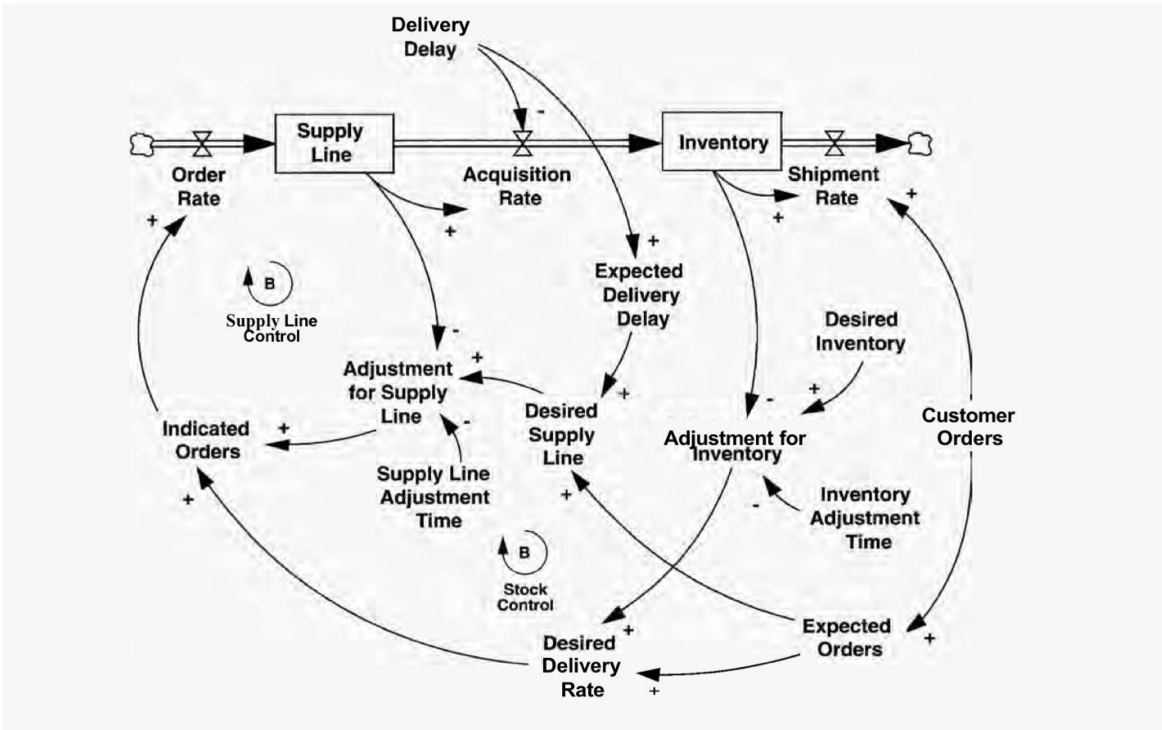

Figure 1. Beer Game Supply Chain Dynamics. Source: Sterman (2000).

The game was developed at the Massachusetts Institute of Technology and has been performed by students and managers with fairly consistent results. The game is played in teams with a player occupying a node along the supply chain with the role of stock management for that node. The game is played in rounds where each player recieves stock, fills backlogs, recieves orders, and fills orders based on rules. Penalties are accrued for backlogs and surpluses with the goal of minizing a team's collective penalties at the end of all rounds. To simulate the relationship with team members further up the chain, there is a shipping and order delay of two rounds between nodes.

The game initates with the first few rounds of the system in equilibrium. Then, for a single round, customer orders increase by 100%. Since corrections take four rounds to impact a supply node, most managers make their next orders based on their current discrepancy without accounting for the corrections already in the system. The usual result is that the students order in a pattern that creates undershoot and overshoot that is amplified up the supply chain (see Figure 2). An important lesson is that poor results are

not a result of bad managers, but that management decisions are a product of the structure and incentives designed into the system (Sterman, 2000; Senge, 2006).

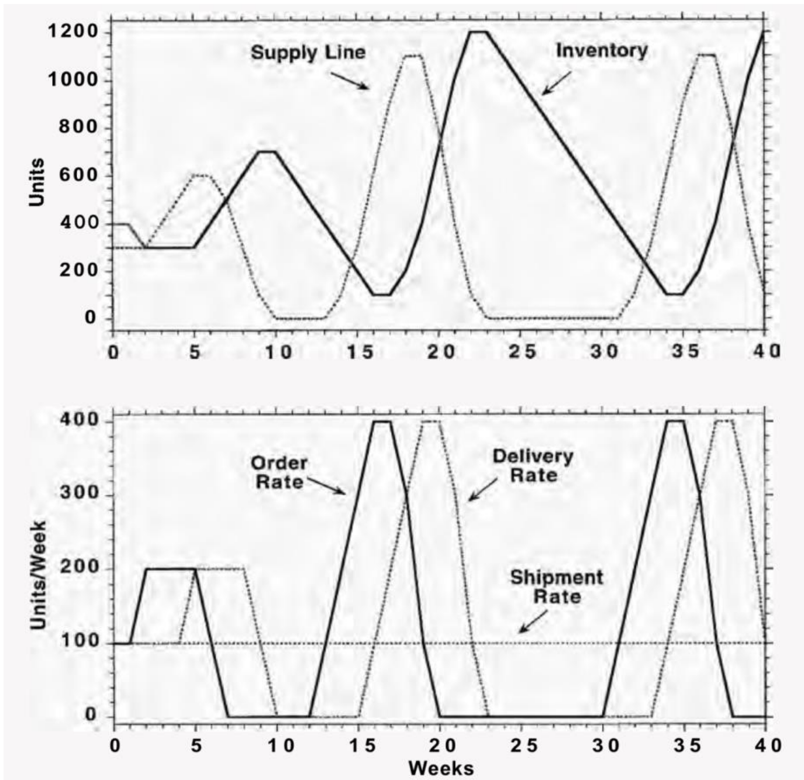

Figure 2. Typical Beer Distribution Game Results. Source: Sterman (2000).

The game is a simplified version of how supply chains are organized in real life. However, it does capture how delayed orders can perpetuate an overresponse in supply. Assuming the objective of a supply chain is to meet an uncertain future demand while minimizing costs, demand forecasting seems like an attractive management tool. But, using this alone can be misleading as demand today does not guarentee the same demand tomorrow. The game illustrates how a small increase shocked the system out of equilibrium. Accordingly, supply forecast built off of demand alone decrease stock stability (Saeed, 2009). This is not desirable for tactical situations, as symptoms of system instability include long wait times, prolonged surges in supply operations, and other inefficencies (Sterman, 2000).

One way to achieve stability through the supply chain is to control the stock objectives, or desired amount of stocks on-hand. These buffers are known to increase inventory stability during operations (Meadows, 2008, p. 150). However, inventory buffers incur costs by increasing the stock management requirements to ensure the material is readily consumable. Resource decisions should take into account the flow constraints and stock objectives of proximate nodes in the supply chain. This can be enforced using proportional, integral, and derivative (PID) control processes that respond to changes in demand in a manner where the system may always be lagging behind the goal, but ocillations in inventory levels are reduced (Saeed, 2009).

Saeed (2009) applied PID in a classical sense (see Figure 3); a feedback loop that proportionally adjusts production rates using the difference between current and desired inventory, plus the area or integral of the error over the period, plus the rate of change in the error (p. 64). The control output is the input production rate during the next period in the sytem. The key difference between PID and typical forecasts used in supply chain management, is that PID is tracking the instantaneous inventory while forecasts use historical demand (p. 74). So, a requirement for PID implementations is a direct link between the state of inventory and the production rate control.

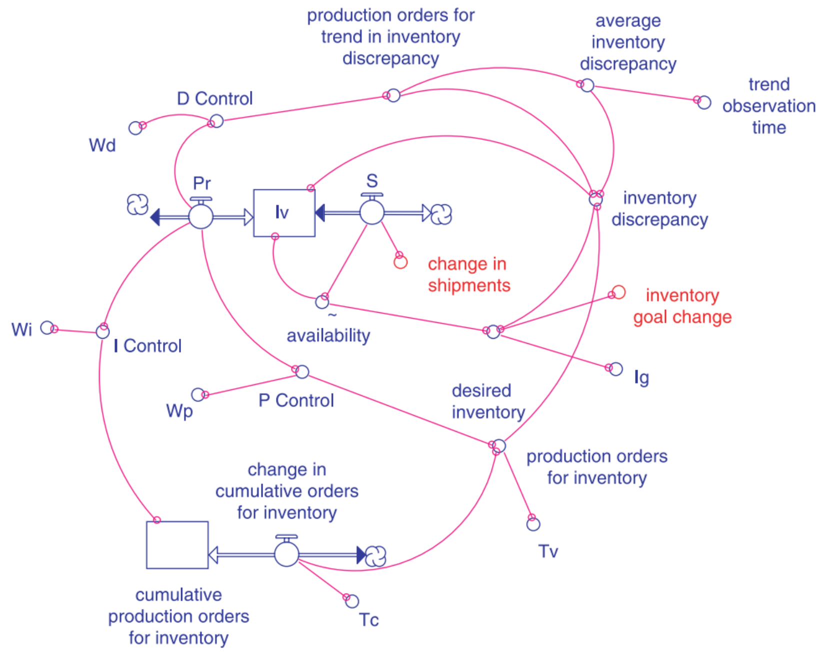

Figure 3. Supply Chain with PID Controls. Source: Saheed (2009).

While wholesale and distributor levels of the tactical supply chain operate from fixed facilities, retailers have to maintain high-mobility balanced with capacity in a tactical environment. These management decisions are constrained physical limits, budgets, and policy. For instance, a 20-foot flatbed can accommodate two sixcon pods, which are modular rigs involved with distributing bulk fluids. A common dilemma in combat is to match the right pod combination to optimally support the mission. Pods can either carry 450 gallon containers or a 150 gallon-per-minute pump (Northrop Grumman, 2010). Demand may exceed 450 gallons for a single distribution mission, but the decision needs to take into account the time allocated for transfering fuel in a combat environment. While 900 gallons seems better than 450, it may take significantly longer to process a queue of vehicles without the pump, so it becomes an optimization problem with an efficiency frontier that trades off between fuel and time.

The capabilities and limitations of stocks and flows can be modeled in systems dynamics mathematically. Stella is a systems dynamics computer modeling application that uses a form of extensible markup language known as XML Interchange Language for Systems Dynamics (XMILE) (Isee Systems, 2016). Stella allows users to create icon-based models that depict stock behavior over time in a system. Models with a single inventory and corresponding inflows and outflows are first-order systems (Sterman, 2000, pp. 281–290). The top of the model represents the stock and flows, while the bottom variables represent less visible decision rules that govern the system (see Figure 4) (Sterman, 2000, p. 669).

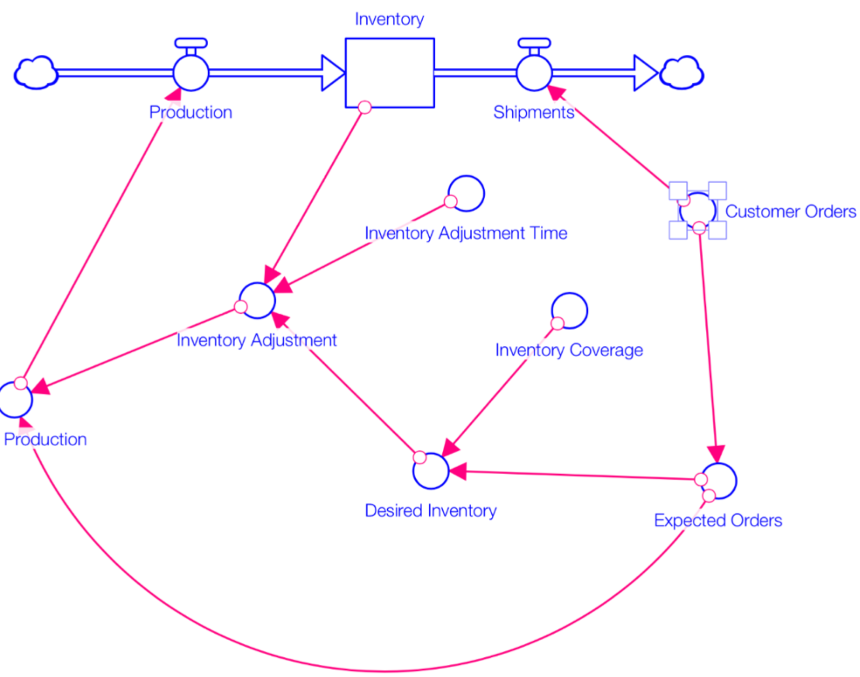

Figure 4. First-Order Supply Chain System. Adapted from Abdel-Hamid (2016).

Chapter IV introduces the mathematics that formulates each of the icons in the experimental design. The icons operate as input/outputs with information following the direction of arrows. The important concept to introduce is that the diagram infers a feedback loop that balances supply and demand. The dominant supply loop is controlled by two decision rules, which are variables that dictate inventory coverage and inventory adjustment times. The demand is controlled with one decision rule—shipments equal customer orders.

The decision rules in the supply loop cause goal-seeking behavior to maintain the inventory at the inventory coverage level. The inventory coverage is a measure of time and the desired inventory is a measure of units; inventory coverage can be replaced with operational reach in terms of the E2C2S. The inventory adjustment is a response to the difference between the desired and actual inventory. The desired production is a forecast based on historical orders, but the response is dampened by the fractional inventory adjustment time.

The decision rule in the demand process proportionally reinforces the customer orders. As customers order more, their order activity increases shipments. Examples of alternative rules that would affect demand include rationing, cost scaling, or surplus objectives. Chapter IV explores the decision rules in the tactical supply chain. The quantitative analysis demonstrates how these decision rules impact system behaviors.

The tactical supply chain can be viewed as a series of first-order systems similar to the Beer Distribution Game. The customer fuel status is represented by the vehicle fuel tank at the lowest level of the system, which can be aggregated to represent the respective unit level demand. There are multiple retailers as fuel is pumped from large bags and mobile tankers on the battlefield. The distributor role in the tactical fuel system would be the inventories kept at large fuel bladders that feed the retailers. The wholesalers would be the theater stocks that are held at major ports and the producers would be the facilities that actually refine the tactical fuel. Between each inventory would be a conveyors such as ships, pipelines, motor vehicles, or heavy-lift rotary aircraft (Northrop Grumman 2010; Hinkson, 2010).

Stella can help researchers visualize the structure and organization of a system. The engine of the program uses mathematical formulations to enable quantitative analysis and evaluation of systems. The following section discusses some of the quantitative methods that are relevant to supply chain management. The analysis of data converges the Stella modeling tool with these methods to evaluate how the telematics may impact operational reach.

2. Optimization

Mathematical models can solve supply chains problems by modeling the flow of material throughout a network. One such model is the logistics inter-temporal network optimization (LITNO), which defines a logistics network into nodes, levels, edges, and periods (Kress, 2002, p. 2435). The model assumes that the number of nodes are be determined by the intensity of conflict. Nodes are points in a system where stocks are stored. The intensity also determines the number of levels, which are echelons in the system hierarchy. Nodes and levels are connected by edges, which are lines of communication. The edges relate to flows as they are defined by rates and capacity over

time. The temporal part of the model is based on the periods, or measures of time used to represent the length of the operation (see Figure5).

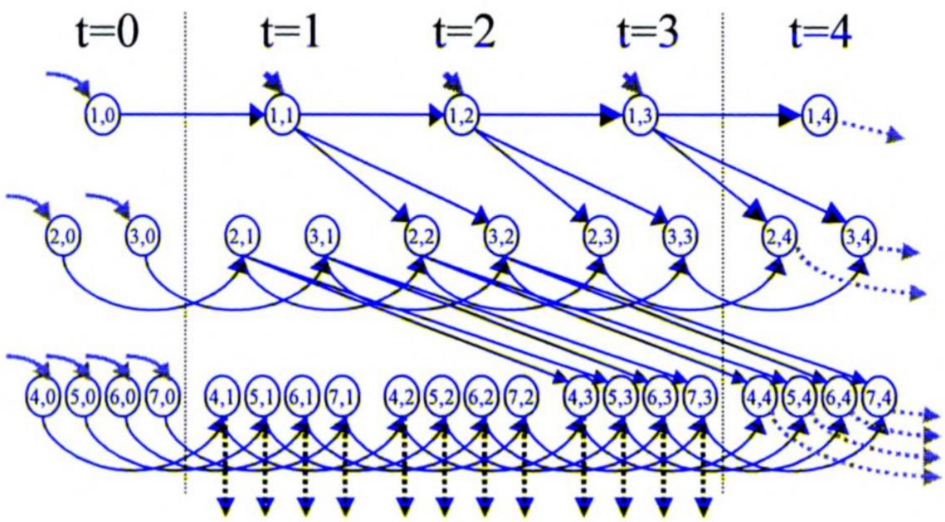

Figure 5. The LITNO Model. Source: Kress (2002).

The optimization model solves a very specific type of computational problem. The model assumes deterministic values for amount of supplies, transportation capacity, consumption, and demand of the network over the specified time (Kress, 2002, p. 2474). The model simulates the interaction of supply and demand, which allows planners to estimate how a logistics network will perform when transportation or supply variables are adjusted. The objective of the model is to minimize the cost to satisfy demands (Kress, 2002, p. 2483). The costs are the units, material, and transportation assets utilized in the model.

The linear programming of the model allows operational planners to design networks that inform the organization of logistics forces, demand profiles, as well as the flow-rate of supplies into a theater of war (Kress, 2002, p. 2624). With demand profiles, time series analysis can be used to understand relationships between causal factors and their explanatory power on the system patterns (Savage, 2003). These demand profiles can be used to evaluate or synthesize goals for a system in the form of desired inventory levels or desired inventory adjustment times (Kress, 2002, p. 2624).

The LITNO's limitations are in its deterministic nature and assumption that information is perfect throughout the system. The model also assumes that information and inventory flow in one direction and that waste just falls out of the system. A later discussion in the chapter will go into detail how this is sufficient when dealing with planning or detailed command and control, but insufficient for managing current operations or mission command and control. System dynamics models can utilize characteristics of linear programming while incorporating solver techniques such as the Monte Carlo simulations, triangular estimates, and feedback loops that can account for dynamic rates over time (Sterman, 2000, pp. 231–239; Savage, 2003). However, the solver techniques are only as reliable as the statistical inferences they are derived from; in other words, dynamic modeling has a garbage-in/garbage-out caveat.

3. Related Studies

The following discusses evidence of causal factors in fuel consumption found in related studies. Supply-side studies focus on response times and distribution methods (Hinkson, 2010; Northrop Grumman, 2010). Demand-side studies focus on how policies can impact consumption rates (Tulusan, Soi, Paefgen, Brogle, & Staake, 2011; Stillwater & Kurani 2012; Corbett, 2013; Kurani, Stillwater, & Jones, 2015). Other studies using grounded theory focused on the interaction of human behavior in the system and its effects on system performance (Salem & Gallenson, 2014; Salem, Gallenson & Aten, 2015).

a. Demand Side Management

The feedback loops that control consumption are discussed in terms of demand side management (DSM), which is defined as "the downstream activities associated with the consumption-end of the value chain, with the objective of understanding, influencing, and managing consumer demand" (Corbett, 2013, p. 749). The DSM strategy objectives fall into two categories: energy efficiency and load management (Corbett, 2013). For E2C2S, energy efficiency looks at how fuel is consumed, while load management looks at the how effectively demands and consumption are being matched.

Based on this approach, the sensor density per capita and the collaborative efforts between consumer and energy providers are the greatest determinants of successful DSM

strategies (Corbett, 2013, p. 756). Corbett (2013) found that one-way automated meter readings from the point of consumption to the energy provider leads to processing waste and a significant negative impact on system performance (p. 756). Without communication and interaction with the consumer based on complementary goals, there is no evidence of increases in energy performance (Corbett, 2013, p. 756; Kurani, Stillwater, & Jones, 2015, p. 48).

Many studies explore eco-driving, which can be defined as ecological or sustainable driving habits, which are focused on measuring the impact driving habits have on the environment (Tulusan, Soi, Paefgen, Brogle, & Staake, 2011; Stillwater & Kurani 2012; Kurani, Stillwater, & Jones, 2015). The primary measure of effectiveness for energy performance is miles per gallon. Other measures of performance include acceleration profiles, braking profiles, and fractional idle times. One study of interest sampled over three million vehicle trips across Europe and provided weights to factors on energy performance. Driver-related factors such as acceleration and braking profiles account for 10–30% variance in fuel consumption. The logistics of the trip accounted for a 50–70% variance in fuel consumption. Most interesting was that temperature and wind speed accounted for up to 100% variation in fuel consumption during trips (CGI Group Inc, 2014). This meant an engine that operated at 13–17 miles per gallon, four miles per gallon of variance, could be expected to operate at 9–17 miles per gallon during a storm. The conclusion seems rational as braking and accelerating behavior may become more aggressive with limited visibility.

There are opportunities to identify and reduce waste through excessive idling of tactical vehicles (Skelding, 2014, p. 24). Overall, the eco-driving studies do not generalize well to the E2C2S objectives. The reason for this is that combat related missions require aggressive driving profiles. The missions require an immediate response to hostile threats and austere conditions in low-visibility or low-light conditions. These driving profiles demand aggressive acceleration and braking to control formations in a manner that favors security and survivability over fuel efficiency. While the solutions proposed in the study may not fit well in a combat role, the development of goals for energy providers and consumers on the battlefield should focus on increased awareness

of fuel consumption, resupply response times, and maximizing the utilization of fuel distribution assets (Skelding, 2014, p. 24).

b. Supply-side Military Studies

There are three particular Marine Corps-focused studies that explore fuel monitoring and expeditionary fuel operations (Chiarotti, 2007; Northrop Grumman, 2010; Hinkson, 2010). Chiarotti's (2007) study provided an initial assessment of how planning and supply-side management of fuel may be impacted by automated sensor reporting. The study identified key benefits of capturing historical mission-based demand profiles to improve the accuracy of fuel requirements. In addition, near real-time information may reduce response times through early detection of critically low stocks (Chiarotti, 2007, p. 56). Northrop Grumman's (2010) study provided an in depth analysis of endogenous factors including fuel equipment specifications and methods to integrate these constraints into a LITNO model over a series of brigade and corps-level scenarios. Hinkson's (2010) contribution identified the benefits of adopting a standard metric to model multi-class distribution systems requirements; he represented all supply and demand in terms of pounds, which then allowed load matching with distribution assets. His study found the greatest factor of a unit's sustainability was in the response time to supply demands (p. 58).

c. Human Factors Studies

Additionally, there are several recent studies that discuss the feasibility of improving energy performance through a portfolio of initiatives that address human factors that impact both supply and demand side dynamics (Salem & Gallenson, 2014; Henton & Noack, 2015; Robison, 2015; Salem, Gallenson, & Aten, 2015). Salem & Gallenson (2014) highlighted the lack of energy awareness and how fuel tracking is ad-hoc and prone to error (p. 30–32). While fuel telematics may mitigate these issues, success is dependent on how the data requirements are formed, integrated, analyzed, and acted on (Henton & Noack, 2015; Robison, 2015). The human factors studies suggest an approach to the acquisition and life cycle management of vehicle telematics that are designed for deep situational awareness (Salem, Gallenson, Aten, 2015, p. 16).

B. MARINE CORPS DOCTRINE

1. Command and Control

United States Marine Corps operations subscribe to a simplified version of Boyd's (1986, 2010) naturalistic decision-making theory (USMC, 1996, pp. 63–65). Boyd's (2010) framework categorized decision making into a four interrelated activities; observation, orientation, decision, and action (OODA) (p. 3). The principal premise reduced from the theory is that "in any conflict, the antagonist who can consistently and effectively cycle through the OODA loop faster—who can maintain a higher tempo of actions—gains an ever-increasing advantage with each cycle" (USMC, 1996, p. 65). The second premise is that "multiple OODA loops spin simultaneously, although not as the same speed, as commanders exercise command and control at their own level and locale" (USMC, 1996, p. 64). The USMC (1996) evaluated operational control of a mission by assessing the tempo relative to the protagonist of their actions (p. 65).

The USMC's (1996) identification with Boyd's (2010) framework is relatable to system dynamics terminology. Boyd's (2010) framework views decision making as a functional process related to many interconnected feedback loops. In terms of systems dynamics, tempo is a rate of change or flow. Each activity accumulates information that is processed that impacts future iterations. The USMC (1996) process simplifies the interconnectedness into a linear cycle (see Figure 6). Boyd's process suggests a more complex and iterative veiw of the process (see Figure 7).

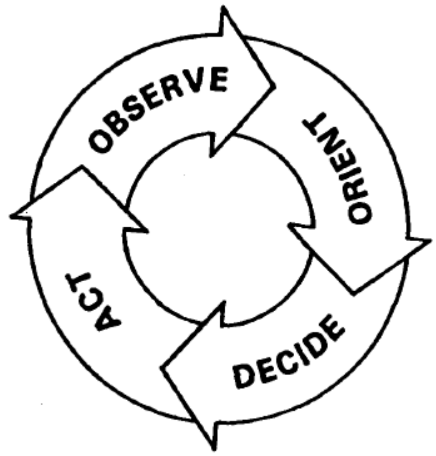

Figure 6. The OODA Loop. Source: USMC (1996).

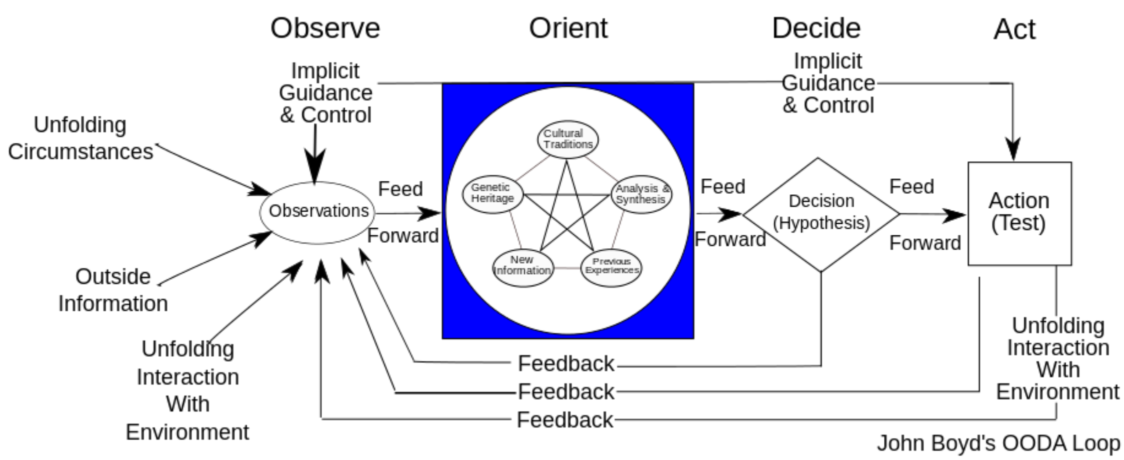

Figure 7. John Boyd's OODA Loop. Source: Boyd (2010).

The USMC (1996) version of the model is a linear cycle where the interdependences of an activity treat the output of a previous step as an input. There is a mechanistic bias in this view, so it may be useful for some problems, but is limited when trying to understand causal factors in the behavior of a control system. Boyd's (2010) model included five interrelated endogenous factors and three exogenous factors, with several feedback loops that suggested nonlinear dynamics. Certain activities will dominate based on the state of the environment and that dominance may shift to other activities as the environment changes.

The following section of the USMC (1996) doctrine discussed the information processing hierarchy as the engine to the decision activity in the OODA loop (pp. 67–71). There is an emphasis on using overview pictures based on image theory, which is the theory that "people generally think in terms of ideas or images— mental pictures of a given situation" (USMC, 1996, pp. 77–78). The discussion suggested that analysis and synthesis processes embedded in the first O of the OODA loop are done with different lenses, and this idea was well defined by Shattuck and Miller's (2006) dynamic model of situated cognition (see Figure 8).

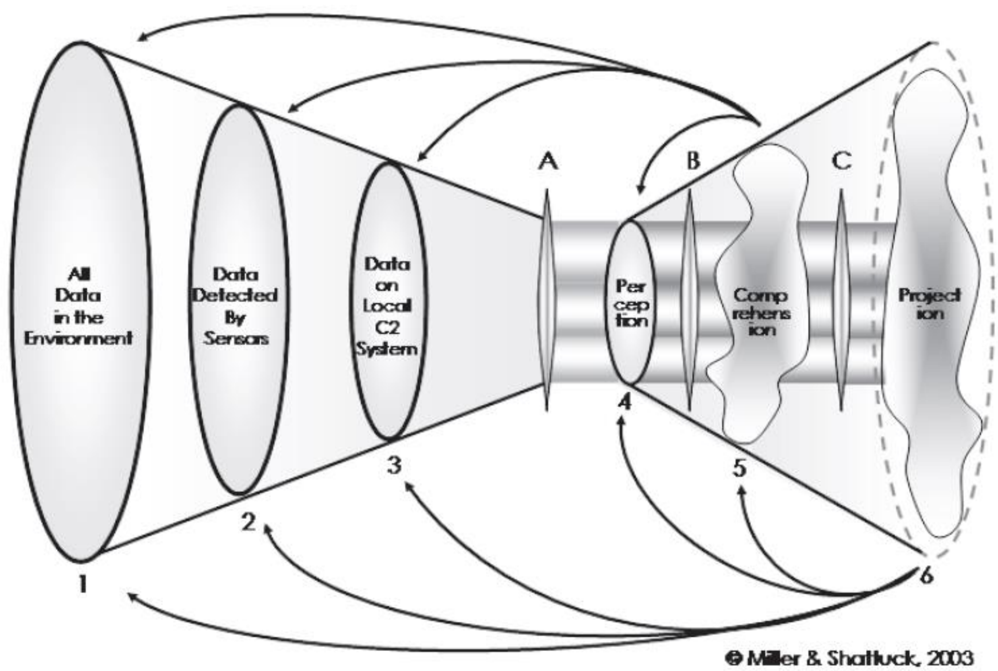

Figure 8. Feedback Loops in the Dynamic Model of Situated Cognition. Source: Shattuck & Miller (2006).

The USMC (1996) understanding of image theory states that information experiences "a certain degree of distortion and delay," as it passes through processing lenses to the decision maker (p. 75). An insight pulled from this concept is that certain decisions have a higher requirement for accuracy and certainty, which agrees with the observation that information has varying processing paths to the commander (USMC, 1996; Shattuck & Miller, 2006). Shattuck and Miller (2006) address the issue of

distortion at the sensor level being due to insufficient numbers, malfunctions, lack of sensitivity, and a lack of specificity (p. 7).

Marine Corps' doctrine on C2 attempts to mitigate these information delay and distortion issues with decentralized control, which is related to the field of cybernetics. The USMC (1996) described the context of mission command and control as having increased uncertainty or entropy in the decision cycle's environment (p. 79). The idea that "discipline imposed from above is reinforced with self-discipline throughout the organization," which grants higher autonomy or decentralized decision making authority is strikingly similar to the concept of optimal decentralization as discussed in the Viable System Model (USMC, 1996, p. 79; Beers, 1985, p. 16). Optimal decentralization is matching the complexity of the environment with the complexity of decisions that can be made at that level of the system—the match measures a variety of sensory states and response states in the actor (Beers, 1985, p. 10). Interestingly, the concept of variety as it relates to sensors is identical to Boyd's (1987) use of adaptability in a command and control systems, which stated that "without variety and rapidity, one can neither be unpredictable nor cope with the changing and unforeseen circumstances" (p. 4). The idea of requisite variety is based on Ashby's (1956) explanation as it related to feedback loops (Beers, 1985, p. 10).

The USMC's E2C2S development addresses sensors that report fuel performance at the platform level. The platforms of interest for this investigation are the motor vehicles. The current sensors are human-machine interfaces that include visual reading of fuel gauges and manual extrapolation of fuel tank stocks (Aten & Gallenson, 2014; McCombs, 2015). These sensors are creating data that is then processed to inform resource decisions commanders make for during operations.

In terms of systems dynamics, the sensor variety can be represented with the use of Boolean logic controllers that factor into flow rates. Best solutions to improve energy awareness on the battlefield will require an analysis of the problem from the perspective mission Command and Control (C2), as detailed C2 assumes only two rates in consumption (assault and sustained) and assumes distribution perfectly meets demand instantaneously (Kress, 2002).

The appropriate approach depends on the observer's point of view in relation to the environment. Kress's (2002) observations were focused on theater-level planning and the E2C2S is focused on tactical-level. This dichotomy is a reflection of nested OODA loops. The USMC (1996) defined this as the "spectrum of command and control in which mission command assumes a probabilistic/unpredictable" nature versus the deterministic/ predictable nature that is suited for detailed command and control (p. 81). For the purpose of this investigation, energy awareness will be viewed from the points of view of an artillery platoon, battery, and battalion commander in battle.

2. MAGTF Staff Structure

The USMC's (1996) document splits command and control into a typology of mission and detailed. The split suggests that problem solving used in planning would be different from the method used in execution. The MAGTF views execution in terms of an operations cycle. The operations cycle occurs within the execution of a plan. There is a lack of literature on how the MAGTF staff and subordinate elements parse this work; however, one gains insight by recognizing that a subordinate headquarters is structured to replicate the functions of its parent headquarters. Hierarchical systems that are composed of identical structures at different scales are known as fractals (Beers, 1984; Capra, 1996, p. 137–142). For information systems, the benefits of fractal organization include process stability and reduced information requirements throughout the system (Meadows, 2008, p. 83).

All MAGTF staffs have functionally aligned structures. On a general's staff, the Operations directorate (G-3), as the name suggests, directs the unit operations. Scale can be measured by the rank of an office. Every general officer's staff has a G-3 directorate, which is led by a colonel. This holds true at the MAGTF-level until you get down to a Marine Expeditionary Unit (MEU), which is commanded by a colonel, in which case the operations section (S-3) is led by a lieutenant colonel. Battalions have a major who runs the S-3, and at the company or battery level, the duty is delegated from the commander to an enlisted operations chief. Some platoons assign an operations sergeant, but the staff at level may be a singular person, which is important to note as a structural boundary. The

decision cycles at the platoon level are as rapid as the cognitive load is so low that they are in a perpetual state of executing current operations.

There are three temporally driven subsections at the battalion level and higher (see Figures 9 and 10). Plans, Future Operations (FOps), and Current Operations (COps) are subsections that have different foci when it comes to disseminating commands and implementing controls. While there is no formal doctrine that delineates these separate sections, it has been programmed into the staff structure in the Marine Corps Total Force Management System (TFMS). The logic separates problem-solving efforts based on the information requirements on hand. These sections are tightly bound to ensure continuity, but they are also tied to other functions, as they are the central control in any unit.

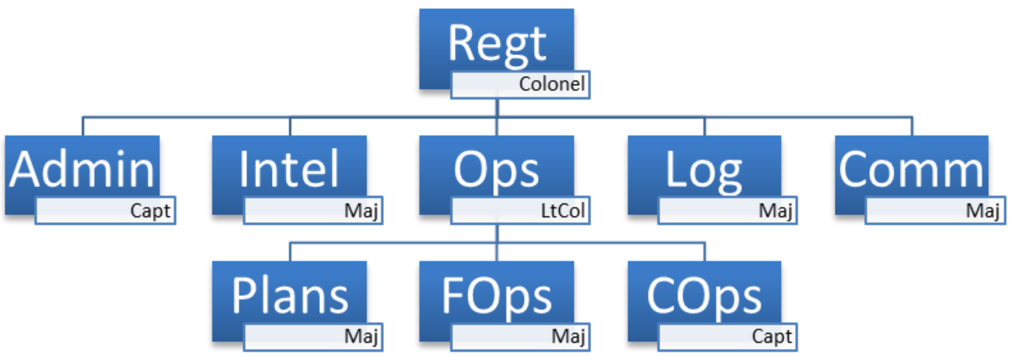

Figure 9. Regimental Staff Structure. Adapted from USMC (1996).

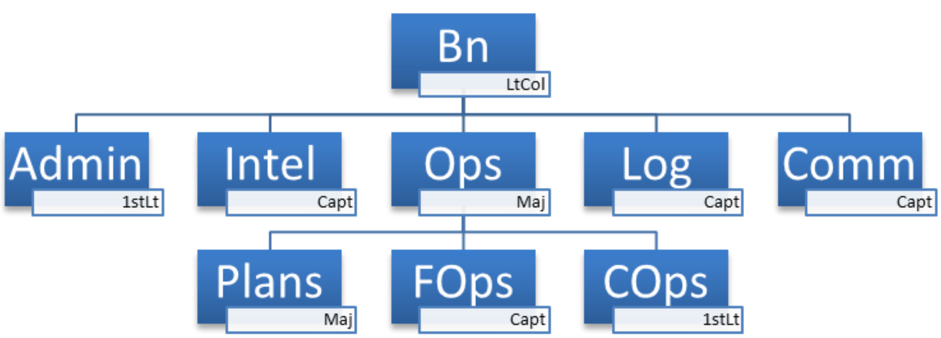

Figure 10. Battalion Staff Structure. Adapted from USMC (1996).

The role of Plans is to create the general concept for how a unit will accomplish a mission. FOps' role is to disseminate orders, direct resource allocation, and synchronize subordinates with support elements. COps' role is to provide real-time control of units in the battlespace, assess progress, maintain situational awareness, and operate decision support platforms. The utility of the self-replicating design above the battalion is in information processing and controls—standardization of staff functions and alignment creates natural input and output points for feedback loops that must traverse through different staff levels. As a decision maker, one can logically anticipate where to get informed, as information management is designed into the organizational structure.

3. Concept of Employment for Artillery Units

The portfolio of doctrine for the training and employment of field units is pertinent to this investigation. Artillery units are typically motorized with the prime movement platform being the Medium Tactical Vehicle Replacement (MTVR), also known as the 7-ton. The USMC assigns a single artillery regiment to each infantry division. Typical task organization assigns an artillery battalion to support an infantry regiment and an artillery battery (equivalent to a company-level command) is assigned to support infantry battalions.

A battery task organization (see Figure 11) typically consists of three platoons—headquarters and two firing platoons. The platoons are divided into two to four shooting sections with three cannons per section. The main artillery cannon is the 155mm M777 Howitzer. These cannons are matched with two MTVRs, a prime mover and a support vehicle. The vehicles carry the troops who operate the cannons as well as the complement of ammunition and powder bags used with the ordnance.

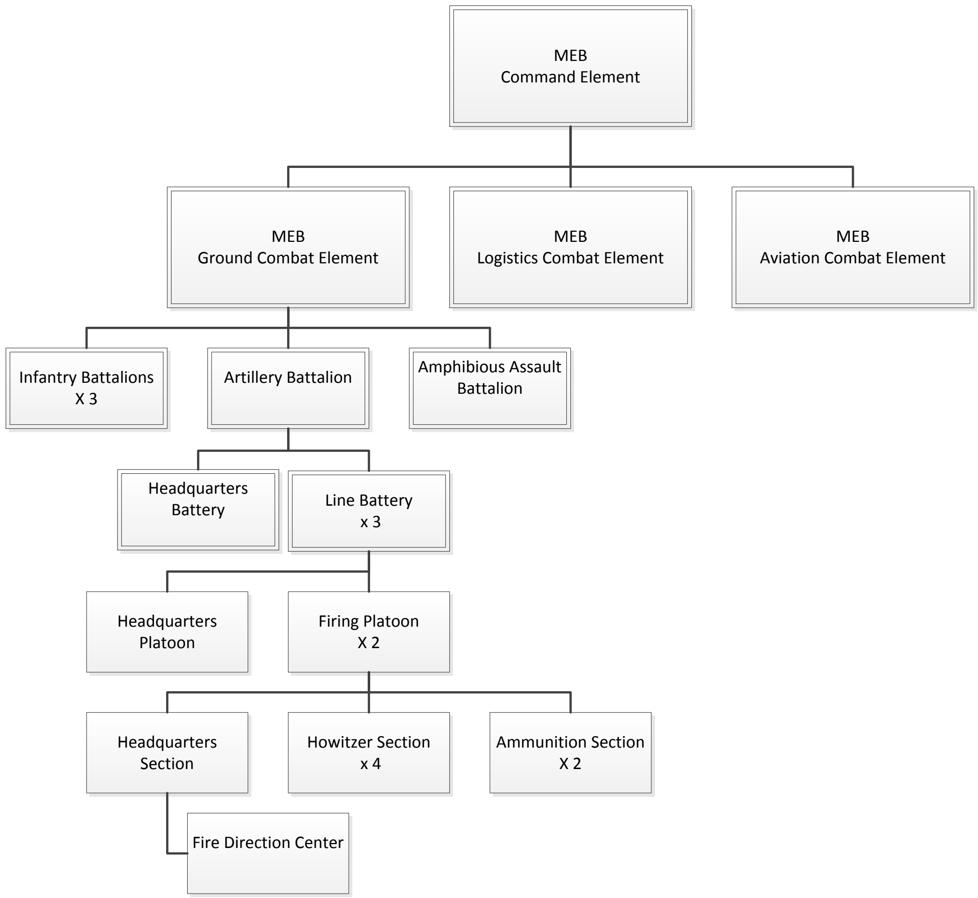

Figure 11. Marine Expeditionary Brigade Task Organization.

The concept of employment typically depends on the variety of firing solutions required by the directing fire support agency. It is typical for platoons to operate with a degree of autonomy. A typical scheme of maneuver will use artillery in the rear area to generate fires to enable maneuver at the forward echelon of the battle area. Before the battle moves forward where maneuver support exceeds the range of effective artillery support, ~35 kilometers, artillery units will echelon gun sections to new firing positions (USMC, 2002 p. 58).

Fuel support is generally coordinated between the battalion logistics section and the battery gunnery sergeant. Planning data is typically drawn from doctrine (see Figures 12, 13, and 14).

Equipment Type	Alaska*	Panama Canal*	CONUS*	Europe*	Korea*
Wheeled Vehicle	7	4	8	10	5
Generators	20	20	20	12	20
MHE	10	20	20	12	20
Stationary Equipment	10	10	10	12	10
* Hours of Usage					

Figure 12. Estimates of Daily Fuel Usage Rates. Source: USMC (2002).

(# of vehicles/equipment) x (daily fuel usage rate)
(consumption rate) = fuel requirement

Figure 13. Fuel Requirement Estimation Formula. Source: USMC (2002).

Vehicle/Equipment	Fuel			Water*
	Rate (gal/hour)	Tank (gal)	Type	Radiator (gal)
M923	11.5	70	Diesel	12
M998	1.7	25	Diesel	7
M936	13.0	139	Diesel	12
Mk923 MTVR	Unknown	78	Diesel	
Mk48 LVS	Unknown	150	Diesel	27
MC4000	4.0	35	Diesel	6
3 kW GEN (MEP-16)	0.6	90	Diesel	11
M12 DECON	3.0		Gasoline	500
*Water usage rates are calculated using factors of 1.0 (hot and cold climates) and 0.5 (temperate climate).				

Figure 14. Consumption Rates and Capacities for Vehicles/Equipment. Source: USMC (2002).

The data is formulated in to clear and simple point estimates to facilitate the ease of use in planning. The MTVR fuel consumption rates are listed as unknown, even though it's the equipment used to haul the field artillery cannons. A principle of fuel resupply that addresses the uncertainty is to refuel at every opportunity (USMC, 2002, p. 130). While the protocol simplifies things for the drivers, it results in a lack of awareness of consumption rates within the chain of command. While there is some discussion of the logistics section responsibilities, information requirements from the battery are not addressed, and it is assumed that these are ad-hoc and dependent on personalities and

experiences in the unit. The takeaway is that there is a different treatment at the theoretical level of mission command and control and actual mission execution. The gap may explain why there is a systematic distortion and error in fuel sensing and response.

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III. METHODOLOGY

A. INTRODUCTION

1. Mixed Methods

Mixed methods research designs combine and integrate qualitative and quantitative methods of research (Creswell, 2014). The approach uses a technique of triangulation of findings between the two methods as a means mitigating bias of a single approach. This study used an exploratory sequential design; the qualitative phase outputs were inputs to the quantitative portion. The outcome of the study provides "an understanding of participant views within the context of an experimental intervention" (Creswell, 2014, p. 231).

2. Exploratory Sequential Design

The exploratory sequential design separated the study into two phases. The qualitative phase collected data for analysis that built into the quantitative phase (Miles & Huberman, 2014). The participant observation examined resource decisions tools that introduced data created by fuel sensor devices through a prototype telematics data-acquisition architecture. The quantitative phase data collection and analysis were designed to test dynamic hypotheses predicting the impact of the telematics may have on the operational reach of Marine Corps units in a tactical environment.

B. QUALITATIVE METHODS

1. Data Collection / Sources

The data collection process began with solicitation of participants who were separated into two categories: subject matter experts (SMEs) on the telematics and Marines involved with monitoring and managing fuel resources. Two SMEs and one Marine consented to participate in the study. A site visit was conducted at a location where Marines and SMEs were training and prototyping various technologies aimed at improving expeditionary energy performance.

The Marine participant was a company grade officer (lieutenant to captain) directly involved with managing fuel operations in a tactical environment. The subject participated in a structured interview, during a three-day site visit, which was designed to extract knowledge of processes that are normally made in fuel resource decisions in a tactical environment. The interview was conducted in a single fifteen-minute session and was recorded and transcribed by the researcher.

The SMEs were stationed out of the same base as the Marines observed in the study. One SME was a warrant officer and the other was a civilian government employee involved in the implementation and evaluation of a commercial-off-the-shelf (COTS) fuel telematics devices. The SMEs served as liaisons for the site visit and were consulted for comments on data interpretation.

Both the researcher and SMEs initiated follow-up emails. Email correspondence occurred over a six-month period. Initial communication concerned logistics and collaborating on subject recruitment for the site visit. During and following the site visit, SMEs provided numerous digital and hard-copy documents. The documents ranged in topic content from previous analysis of fuel operations, engineering and design of telematics architecture, to detailed schedules for the development and testing of technology.

The researcher conducted participant observation during a three-day site visit. Observations were recorded via mixed media, which included seven pages of paper field notes and sketches, an audio recording of the Marine interview, a digital page of notes on Microsoft OneNote, and photographs of telematics devices and fuel logs observed at the field training sites (see Table 1).

The exploratory phase continued after the site visit with a collection of extant literature including previous studies of fuel consumption, studies of dynamics of supply chains, archetypes of complex systems, and open-source policy and guidance published by Department of Defense offices concerned with innovating battlefield power and energy management.

Table 1. Data Source, Item, and Contribution to Analysis.

Data Source	Item	Contribution
Field Notes	Platform Mission based fuel profile sketch	Departure point for building consumption parameters
Field Notes	Data attributes from AIM/BUS	Data engineering concept of key values used to join database tables on fuel performance and vehicle mission tasks
Field Notes	Causal diagram	First prototype of causal diagram to design fuel model
Field Notes	Stock and Flow	First proto of stock and flow of amphib MEB/ESG fuel source and sinks
Field Notes	Network diagram of BUS to data warehouse	Network interfaces at layers 1 - 3 (TCP/IP) stack
SME	UEM AAR Report	Provides account of process engineering issues with fuel accounting procedures - provides current process
SME	LAWST info sheet	Model for tracking fuel and distributions
SME	ScanGauge artifacts	Gave an overview of how it added a tool to the vehicle user interface to visualize and track fuel performance data based on costs - offered that it was received with a low opinion and adoption rate
SME	MPEM info sheet	Turns out its more focused on grid planning and optimization
Participant	Exercise Marine Interview	Account of field processes for fuel performance and accounting
SME	Energy C2 POA&M	Design of experiment, structure, and concept of employment
SME	Vehicle report	Shows how data gets compared from CAN bus samples; 102 entries
SME	NAVSEA ITX 3–15 Report	Shows how analysis generates fuel performance of unit by vehicle type.
SME	CAN BUS extract sample	Provides txt file that appears tab delimited that shows the syntax of the data pulled off of the sensors and stored on the vehicles.

2. Data Analysis Approach

The initial analysis of the qualitative data involved diagram mapping. The data collected was reviewed over multiple iterations to map processes (Miles & Huberman, 2014). Diagram mapping was used to visualize stages of processes for the As-Is process (Meyer, 1991). Subsequent analysis joined these diagrams with literature to derive meaning.

Meaning was drawn from the data and process maps using an inductive, grounded approach (Strauss & Corbin, 1990). The researcher reviewed interview transcripts and extant literature, iterating between the two to identify themes and patterns related to fuel and energy performance. Categories suggested by extant literature included demand side management and supply side management functions in which processes interacted. The As-Is case was compared to optimized supply chain cases and identified subcategories of decision variables such as inventory coverage times, expected and actual delays, expected and actual order rates, inventory adjustment times, and forecasting.

The qualitative phase findings were extrapolated into an As-Is model of fuel supply management. This was the input for the quantitative phase, which informed the experimental design, dynamic hypotheses, and measures for collection and analysis (Creswell, 2014).

C. QUANTITATIVE METHODS

1. Data Collection / Sources

Findings from the exploratory phase of the research were used as the initial data samples for the quantitative collection (Creswell, 2014). Modeling cases were sampled and based on similar categories and subcategory properties; a system dynamics supply chain model was selected as a baseline (Sterman, 2000). Extant literature on the capabilities and characteristics of fuel systems in the Marine Corps were used determine the subject for the experimental design (Northrop Grumman, 2010).

Data was pulled from the Marine Air Ground Task Force Power and Energy Modeling (MPEM) software to develop accurate order rates for the subject in the

experimental design (GroupW, 2015). Studies on Marine Corps fuel consumption were reviewed to triangulate this data for validity (Chiarotti, 2007; Northrop Grumman, 2010).

2. Data Analysis Approach

The hypothesis is that telematics increases operational reach. Independent variables include information delay and level of data integration; the dependent variable being the MAGTF's days of supply. The independent variables interact to form dynamic hypothesis. The Sterman (2000) calls for testing all combinations. This was done with the understanding the hypothesis implies more confidence of the causal effects identified by the researcher. This is different from the hypothesis "telematics affect operational reach," which would suggest less certainty as its non-directional about the positive/negative relationship between the independent and dependent variable.

The data analysis approach for this study replicates the systems dynamics case study of supply chain dynamics in the Beer Distribution Game (Sterman, 2000; Senge, 2006). The problem articulated for the study was used to inform dynamic hypotheses that would test the potential impact of fuel telematics on the fuel distribution system (Sterman, 2000). A simulation model was formulated of the As-Is and To-Be systems relying on the data and findings from the qualitative phase of the study.

The two models were tested for validity by eliminating extraneous variables. Also, the model variables were set to extreme circumstances to test for reliability. The decision variables were evaluated for ability to realistically represent data that would be used by managers in a tactical environment.

After model validity was addressed, the dynamic hypotheses were tested. The independent variables were adjusted and the dependent variables were measured. Sensitivity analysis was conducted on the relationship between variables. These were contextualized against the quantitative performance of the supply system.

The findings of the quantitative phase of the study were used to evaluate policy design for the implementation of fuel telematics in tactical vehicles. Based on the performance in the model and lessons from extant literature, conclusions were drawn about the outcomes of the tests.

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IV. ANALYSIS

A. QUALITATIVE ANALYSIS

1. Introduction

According to the Expeditionary Energy Office, the purpose of the Expeditionary Energy Command and Control System (E2C2S) is to control the supply and demand of energy with an objective to maximize the operational reach of the MAGTF (Daniels, 2015). Vehicle telematics are being explored within that purpose. The supply-side process can be represented as the flow of liquid petroleum from wholesale sources to vehicles. The demand-side process deals with processing transactional orders that close when fuel is delivered. This chapter describes the As-Is demand transaction life cycle, which will illuminate information delays and distortions that are targets of the fuel telematics interventions which will be enumerated further in the To-Be Process.

To build off of Chapter II's introduction to the G/S-3 functions, the logistics (G/S-4) staff functions are key in transitioning demand from the customer to the retail-level supply commodity. The internal actions that a field unit performs to sustain operations are considered logistics operations. The G/S-4 section of a unit manages parallel operations that are integrated with the G/S-3 through synchronization processes that are both formal and informal (see Figure 15). One of the activities that synchronizes operations with logistics is distribution management.

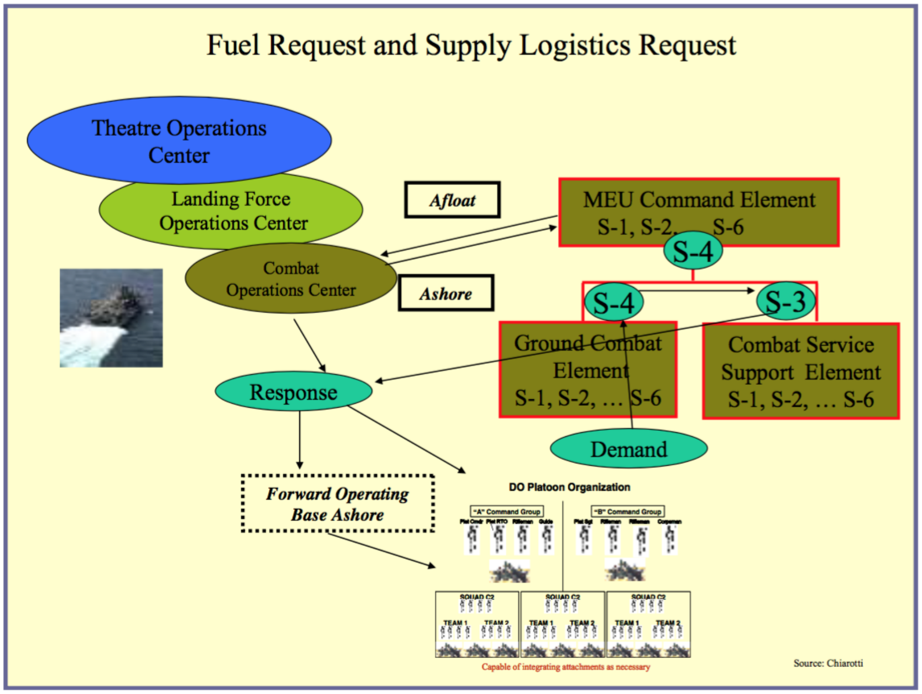

Figure 15. Relationship between S-3 and S-4s within a MAGTF.
Source: Chiarotti (2007).

Distribution is a function that integrates supply operations with transportation assets. The wholesale and distribution of fuel are performed in a MEB by the Logistics Combat Element (LCE). Distribution management is executed in an activity that is organized under the G-3 and staffed by G-4 personnel (see Figure 16). The LCE is the main provider of maintenance, supply, engineering, transportation, medical, and services to the MAGTF. While all battalion S-4s manage the internal logistics requirements that correspond to these functions, the LCE S-3 directs activities that fulfill those requirements through two methods of support, which will be detailed in the following sections.

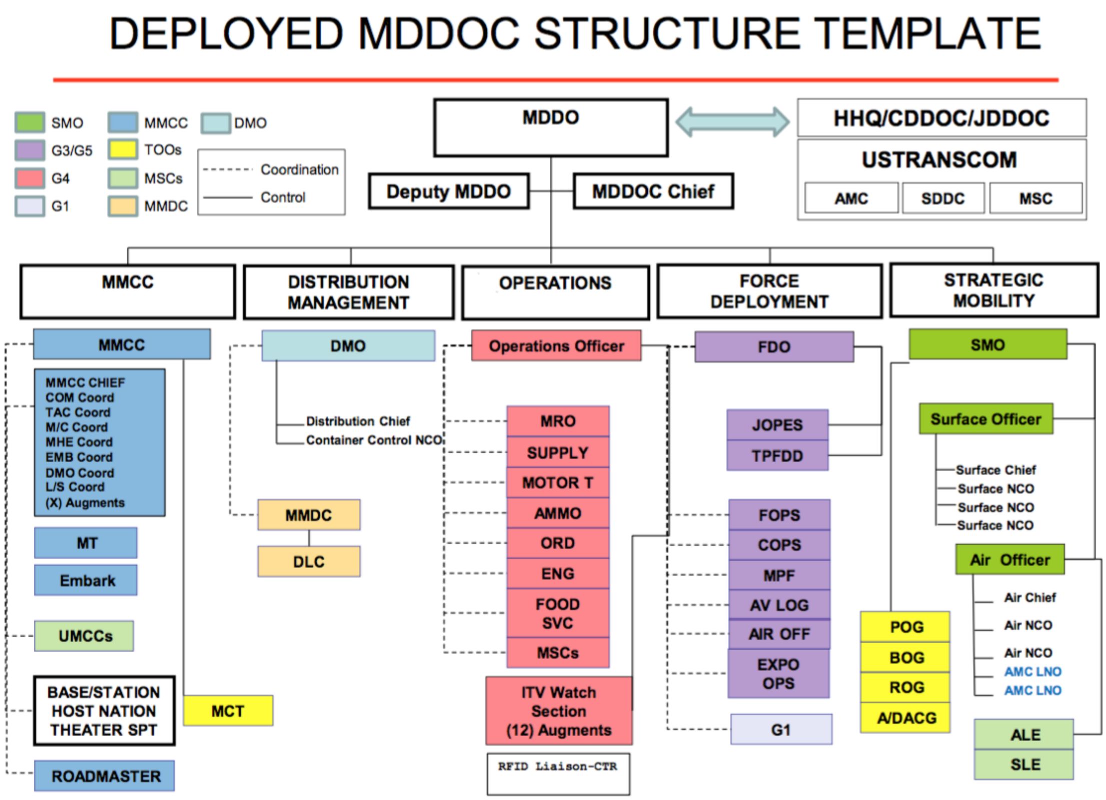

Figure 16. MAGTF Deployment and Distribution Operations Center Organization. Source: USMC (2014).

The As-Is process is generalized as a fuel supply chain based on system dynamics modeling that captures fuel inventory from the vehicle platform up to the battalion logistics section. This model shows the dynamic interactions of fuel distribution with information delays that communicate demands through the various levels of stock in the MAGTF. The theoretical time delays and other information processing factors are based on data collected from observations and documented accounts of MAGTF operations. Scientific studies on fuel consumption factors provided evidence for aspects of the model that did not exist or lacked scientific validity in military accounts of the process.

Since 2007, the Marines have been developing a To-Be process to better control energy on the battlefield. The objective of increased energy awareness has prompted an examination of a range of technology-based solutions. The benefits and limitations of these technologies are described in terms of potential impacts on the As-Is process. The

result informed a model that used system dynamics to demonstrate the potential impact of fuel telematics on the supply and demand of fuel for tactical vehicles.

The model is used as an input to the subsequent chapter's experimental design that measured and compared the As-Is and To-Be processes. This was done in terms of stock behavior as it relates to internal and external factors that regulate the performance of each respective system. This chapter establishes evidence for the experimental designs with a foundation in concepts of communication, cybernetics, and systems thinking introduced in the previous chapter.

2. AS-IS TACTICAL FUEL OPERATIONS

a. The Information System

The As-Is tactical fuel operations are controlled by an ad hoc information system which includes the people, processes, hardware, sensors, and data that manage fuel resources on the battlefield. To gain a better understanding of energy awareness and consumption, the following discusses major consumption factors and how those factors are related to one another within the system. This establishes what causal effects have the greatest impact on vehicle fuel performance in the context of this study. How the system processes the information about fuel will be connected to the overall operational reach of the MAGTF.

Within this system, one can relate environmental factors to engine loads, engine loads to fuel consumption and conflict intensity, and fuel consumption to a feedback loop that balances fuel demand with fuel distribution (see Figure 17). Information requirements for the system are created in the planning phase. The information processing requirements are a part of the fuel demand management. The fuel demands create fuel distribution missions that lead to issue and receipt of fuel. The objective of the tactical fuel operations is to minimize fuel demands through distributions. This optimization is qualitatively based on the system's ability to perform within flow, capacity, and response-time constraints at various nodes in the system. The overall system can be seen as a series of second-order nonlinear supply chain that balance distributions of fuel with the demand of fuel.

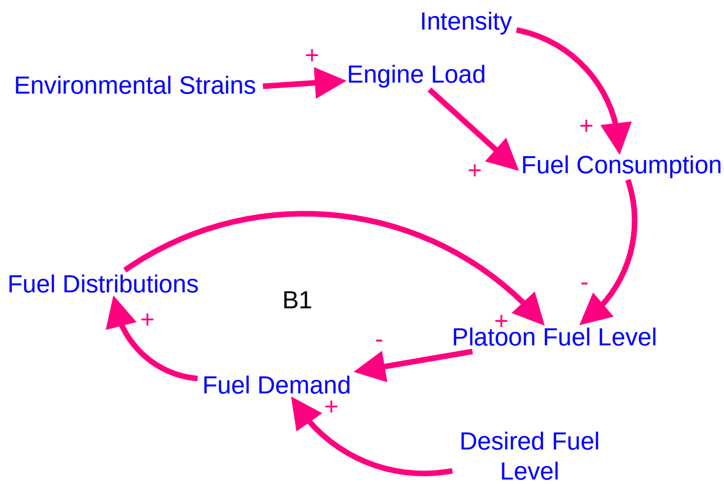

Figure 17. Demand Cycle Causal Loop Diagram.

There is usually a proportional relationship between a consumption rate and inventory being consumed. For example, when a fuel tank close to empty, a driver will avoid excessive braking or acceleration to conserve what is left. However, when you aggregate a platoon of vehicles, the platoon commander may not have an accurate sense of the platoon's inventory and may assign tasks that are not conservative when stocks are low. The knowledge also allows a manager to assign an urgency of need or required delivery time for resupply, but a challenge that emerges in the current system is that suppliers and consumers of fuel are not tightly coupled when it comes to sharing information (Chiarotti, 2007; Reeves, 2014). Information flows one way in the system; consumption turns into demand, which turns into distributions and these reduce demands. Ideally, delays or a lack of distributions would be linked to consumption, a self-regulating system would avoid running out of fuel. However, there have been observations of units operating without energy awareness and exhausting fuel stocks without prior realization.

b. Fuel Planning

There are two types of plans in the Marine Corps: deliberate and rapid response. Deliberate plans have longer time horizons that may begin refining fuel estimates months before operations take place. Rapid response plans, by contrast, have a short time horizon

with a finite set of predefined support packages. Rapid response plans are template responses to emergent contingencies and are executed in a matter of hours after notice. Deliberate plans are suited for brigade-level operations since these organizations are designed to handle high intensity conflicts that last up to 30 days without external resupply.

While units at all levels participate in deliberate planning, a campaign's plan is issued by field units at the regimental level or higher. Deliberate plans include concepts of support and annexes that account for the sustainment of fuel throughout the operation. Based on the operational design within the plan, fuel requirements are estimated based on the unit type, equipment, and intensity of the conflict day-by-day. For an artillery battalion consisting of three line batteries and one headquarters battery, fuel consumed daily would be 3,341 gallons for the assault rate and 1,954 gallons of fuel for the sustained rate in 2007 (Chiarotti, 2007, 67). However, those estimates increased to 16,749 gallons for the same unit's assault rate and 15,927 gallons for the sustained rate in a modeled scenario (Northrop Grumman Information Systems, 2010, p. 319). The most recent planning tool estimated a daily 9,616 gallons in the assault and 9,061 gallons at the sustained rate (GroupW, personal communication, April 22, 2016).

In planning, fuel consumption rates are based on an average rate of gallons per hour per piece of equipment assigned to the unit. An assault rate is defined as 12 hours of consumption per day and the sustained rate is defined as eight hours of consumption per day (Chiarotti, 2007, 67). The Northrop Grumman (2010) study included various hours per day for equipment throughout the MAGTF scenarios (p. 74–75). The change was a best effort to provide a better approximation to "grossly outdated" data being used in the field (Northrop Grumman, 2010, p. 66–75). An assault is "to make a short, violent, but well-ordered attack against a local objective, such as a gun emplacement, a fort, or a machine gun nest" (Joint Chiefs of Staff [JCS], 2016, p. 16). Sustained refers to the rate required "to maintain and prolong operations until successful mission accomplishment" (JCS, 2016, p. 230).

The concept of support addresses fuel sustainment in terms of stocks held at distribution points as each day progresses in the deliberate plan. The distribution points

are typically designed to match supported units to doctrinal sources of support. For example; an infantry regiment can be matched with a direct support combat logistics battalion, supporting companies may be matched to supported battalions, and supporting platoons to supported companies. The simplicity of the arrangement allows for units to be sustained with fuel by decentralized units with minimal oversight. This static plan allows for a synchronization of distribution assets that will flow fuel and distribution assets from their current locations to the planned locations.

There are generally four static fuel points in a MEB's battlespace. The main distribution point is the Amphibious Assault Expeditionary Fuel System (AAEFS) (Northrop Grumman, 2010). This fuel farm feeds two other major fuel points. The second is located in the Combat Logistics Support Area (CLSA), which is where the forward LCE supports ground combat operations. The third fuel point is at the Expeditionary Airfield and is the Tactical Airfield Fuel Distribution System (TAFDS). The TAFDS is a supply node that connects to the Forward Arming and Refuel Point (FARP) that employs the Helicopter Expedient Refueling System (HERS).

As stated before, the doctrinal planning factors are integrated into deliberate plans months in advance of execution. Refinement of the plans occurs as forces and fuel are marshalled into theater. Generally speaking, deliberate plans transition from the operational to the tactical 30 days before execution. Typically, the transition is manifested in subordinate MAGTF elements generating deliberate plans based on the higher headquarters taskings. This *nesting* of plans is thought to ensure a unity of effort. Changes are dissiminated from higher headquarters in the form of fragmentary orders for operations.

c. Future Operations

In fuel sustainment, annexes are seldom updated. Rather, higher headquarters publishes guidance via informal channels such as email or chat. Inside of 30 days before fuel is delivered to a platform for consumption, the planning process takes place through ad hoc or scheduled collaboration. These processes are fed by logistics status reports that are updated daily. In more mature systems, the collaboration is controlled by automated

logistics information systems such as the Common Logistics Command and Control System (CLC2S) that can be updated in real time, but are analyzed on a daily cycle.

d. Current Operations

The following sections will describe the supply chain dynamics of the As-Is tactical fuel system. The activities that are focused on demand side management are referred to as fuel demand management and the activities that are focused on supply side management will be referred to as fuel distribution management. The integration and assessment of feedback between the two activities are referred to as bulk fuel command and control. The description of current practices will highlight information delays and distortions, which are target variables for fuel telematics in the E2C2S system development.

e. Fuel Demand Management

Demand is accounted by measuring fuel distributed to a vehicle or tank, which serves as feedback into the system. The data attributes typically include the vehicle serial number, company or battalion, time of receipt, and quantity distributed. The essence of demand management is ensuring that units are consuming fuel at expected rates and that fuel flows in the system are flexible enough to meet unforeseen changes to demand. However, Marines seldom compare demand forecasts to actual demand.

Demand management of fuel is achieved through a process of synchronization and controls that are established through support relationships within the MAGTF. A demand forecast enters the system in the form of an order for fuel from a battalion S-4. However, this information can be old and subject to time pressures placed by a desired immediacy of the chain of command (see Figure 18). While the data moves up the chain, the unit continues to burn fuel. To try to get ahead of this delay, the orders for fuel are projected two to three days ahead of required delivery based on inaccurate, distorted, and late information (Aten & Gallenson, 2014). The more mature MAGTF systems will utilize forecasting based on historic demands, which are known to only increase instability in the system (Saeed, 2009).

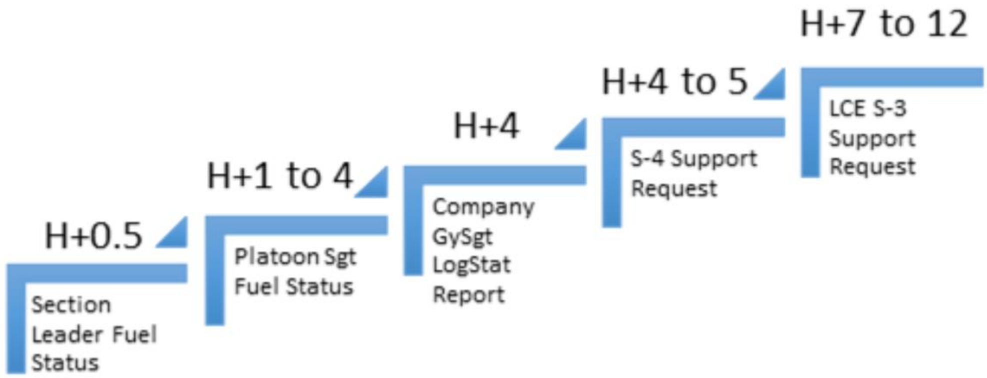

Figure 18. Hypothetical Information Delay by Hours.

The flow of information up the hierarchy is not only delayed, but it is distorted as different levels require conversions of data to different metrics. The information being reported deals with energy stores. The standard measure is gallons of fuel, as this allows for energy demands to be matched with supply (see Ch. II, p. 12). The information is distorted in three separate stages as it goes from the vehicle to the support coordination activities. The stages involve data synthesis, interpretation, and filtering. The purpose of the process is to get information to resource decision makers in a manner that attempts to balance simplicity with actuality.

The first stage takes place within a vehicle section (see Figure 19). The driver visually reads the fuel gauge and assesses the fuel status. The data is mentally stored and may be verbally transmitted based on hitting what is perceived as an unanticipated low-status as feedback which queries if the level is sufficient to make it to the next fueling opportunity. The driver typically interprets the fuel level as a fractional with step intervals from 1/8 to 1/4 of the tank capacity. The vehicle usually filters this status into one of four states: black (0-25%), red (25-50%), yellow (50-75%), and green (75-100%). At no point in this stage does the data read gallons.

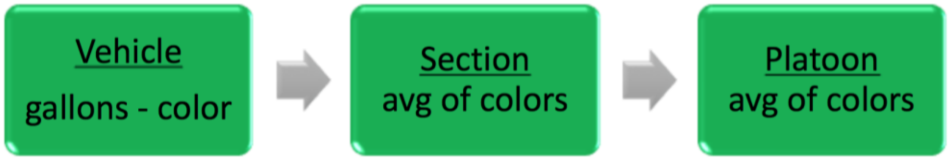

Figure 19. First Stage of Demand Reporting.

The second stage is within the platoon. The platoon sergeant receives data from the section leaders, which is an average color of vehicles in the section. At this point, any unexpected colors are queried for details to evaluate the risk of running out of fuel. If the state is acceptable, the section leader makes a mental note, which is the average color of the sections. The information is relayed to the company as a color with details on any issues that require immediate attention.

The final stage of demand reporting occurs between the company and battalion. There are scheduled daily logistics status reports and unscheduled rapid requests. The report gives a status of fuel in days of supply (DOS). A DOS is calculated by taking the quantity on hand and dividing it by the average quantity used in a day (Chiarotti, 2007, p. 27). DOS is significant parameter as it functions as the inventory coverage time (see Ch. II, p.). The issue with DOS is that it's always inaccurate as it is based on an average (Savage, 2003, p. 67–79). Savage (2003) suggests that a point estimate is only good for decision support if it comes with the variance and the knowledge of the sampling period. Standard reports at this level do not describe variance or the period averaged.

Understanding the variance gives a decision maker insight on the risk involved by acting on the estimate. The variance represents how much error can be expected in a forecast, which puts a fuel demand manager in a difficult position. Given the information delays and distortions, how does one avoid the worst-case scenario without even knowing this window? The worst case is a unit running out of fuel that results in the loss of life or endangers mission accomplishment. So, it would be rational for demand managers to overestimate the requirements rather than underestimate as demonstrated by Chiarotti (2007) (Figure 20). The immediate consequences of this behavior are none. But, overestimation puts more convoys on the road and burns more energy moving unneeded fuel, reinforcing the lack of efficiency in the system.

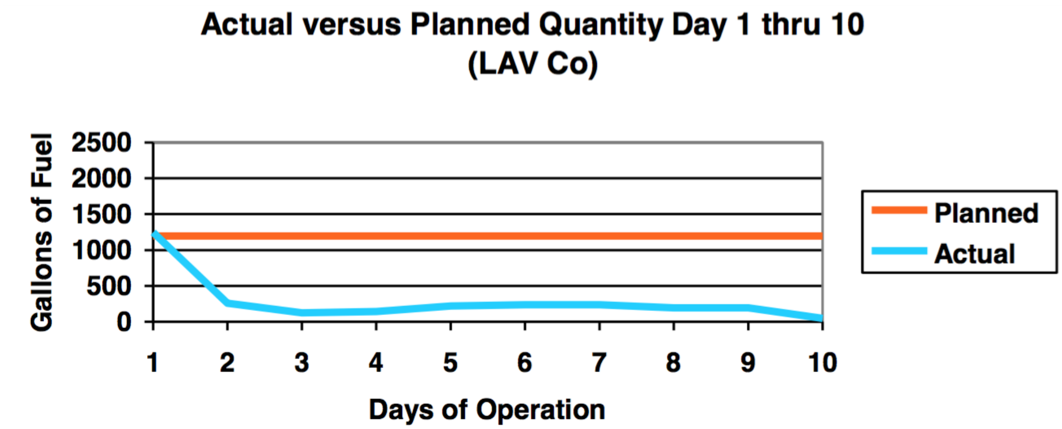

Figure 20. Estimate versus Actual Error. Source: Chiarotti (2007).

f. Fuel Distribution Management

Based on forecasts and registered demands, the LCE will flow bulk fuel distribution assets into the rear area. These assets are categorized into storage and transportation assets. A storage asset is an intermediate tank or bladder that ranges between five and 50,000-gallon capacity. Storage assets with less than or equal to 5,000 gallons are capable of mobile loading. Transportation assets are platforms capable of mobile loading storage assets and delivering them to directed supply points on the battlefield. Examples include the MTVR, Logistics Vehicle Replacement Systems (LVSR), and the Semi-Trailer Refueler (M970). An asset that is categorized storage and transportation are pipelines. These include rigid and flexible hoses that vary in volume.

Fuel distribution management at the battalion level is considered tactical fuel operations. That means the objective is getting fuel into the tanks of combat platforms using retail distributions. The unit S-4 will coordinate with the LCE S-3 to direct fuel resupplies to times and locations of subordinate units. After the supported unit issues the fuel, the supported unit uses the next logistics status report to record their demand, and the logistics section closes out the logistics support request to the operations section of the LCE.

For sustainment lasting more than a few days, the LCE typically assigns a mobile tanker to temporarily attach to the supported unit. This is considered a service station method or point distribution as the mobile tanker functions as a temporary gas station.

The tanker will stay on station until fuel is depleted to 50%, at which point the supporting section heads back to fuel farm to top-off their tank and then return.

The alternative resupply method for pushing fuel forward is *tailgate* issuing. The method involves the supporting unit linking up with the supported unit at a predetermined location. The mobile tanker fills the supported unit vehicle tanks and spare jugs and then completes the mission. In both cases, the fuel distributions are recorded by hand on standardized forms or in log books. The logs are used to account for fuel distributions and in training environments units are billed training funds based on the amount issued.

g. Bulk Fuel Command and Control

The quantity and urgency of demand are controlled by the priority of support. This priority is assigned by the MAGTF commander, via the MDDOC, as a means to rapidly resolve conflicts in resource allocation decisions. The supported units will send representatives daily to confirm outstanding orders or Logistics Support Requests (LSR). The LCE S-3 will take these inputs and create a logistics synchronization matrix. The matrix shows all the support actions scheduled to assigned support units to supported units. The matrix is used to validate logistics support requests that are received from the logistics sections of supported units.

Once the units agree that the matrix is validated for support, the requests are translated into Logistics Support Orders (LSO) and tasked to transportation and supply units for action. A typical fuel distribution mission will involve a convoy, which includes fuel, to execute a distribution at a control point coordinated with the supported unit. The mission cycle includes two fuel demand signals (see Figure 21). The first is the bulk fuel that is going to the rapid replenishment point. The second demand signal is the retail fuel that is being distributed to the supported units before marshalling and after returning.

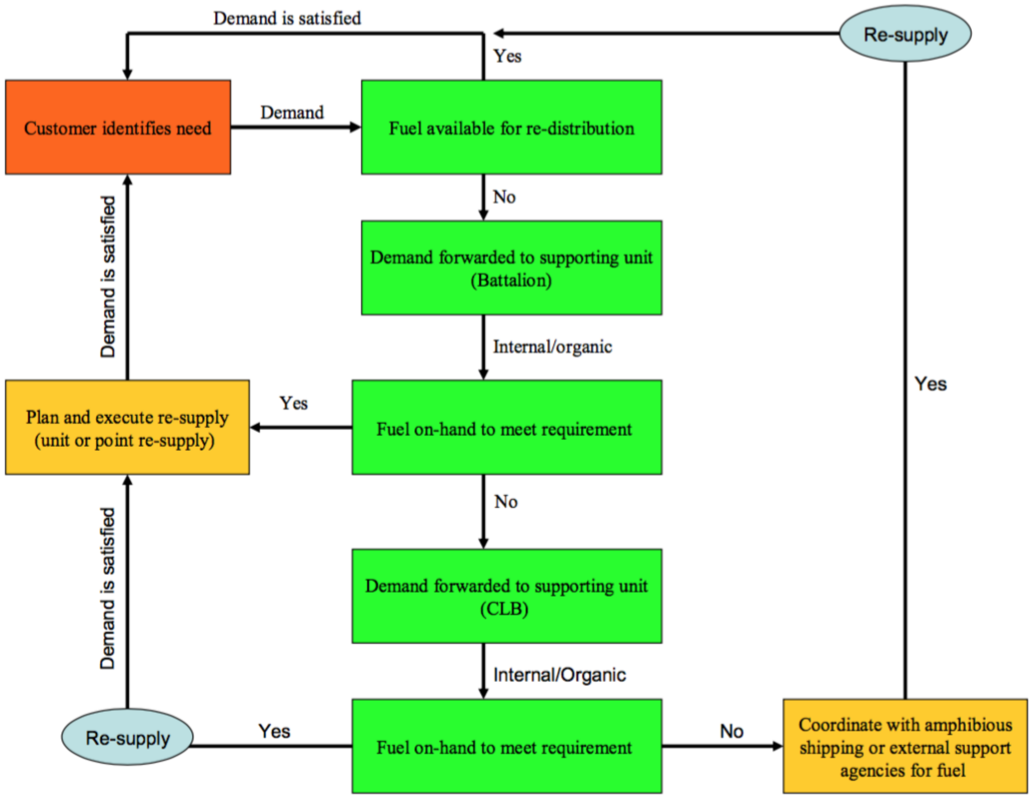

Figure 21. Typical Fuel Distribution Mission Cycle. Source: Chiarotti (2007).

3. TO-BE TACTICAL FUEL OPERATIONS

The objective of the E2C2S system is to maximize operational reach of the MAGTF through improved situational awareness and controls. The integrates different network components interact to form a cohesive system that acquires data and seamlessly delivers it to the MAGTF C2 node (see Figure 22). The concept builds off of several science and technology efforts to explore how logistics can be modernized on the battlefield, the key assumption held is that logisticians with perfect information and the right tools can meet demands as they emerge.

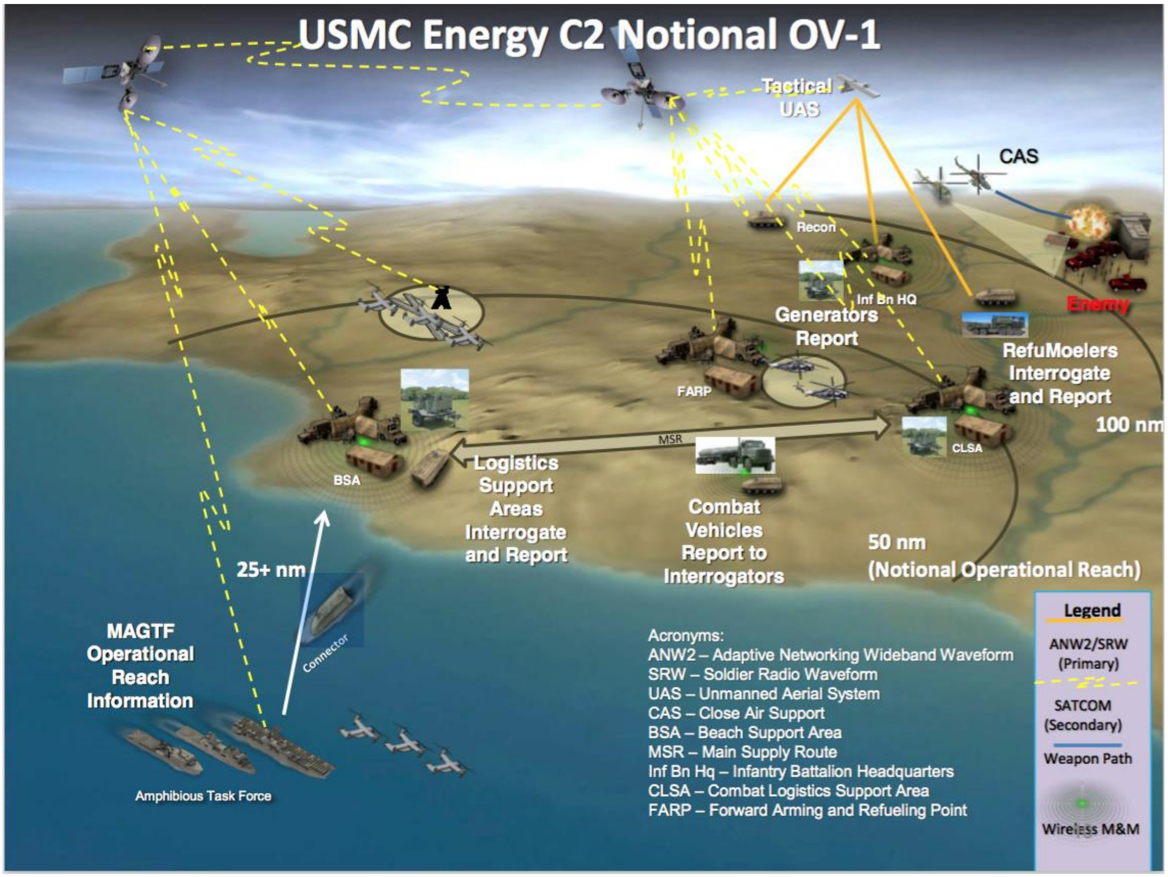

Figure 22. Overview of Expeditionary Energy Command and Control System. Source: Prato (2015).

a. Data Acquisition Technology

In order to bring the concept into practice, there has been incremental development of sensors and network technology to create better information with a seamless path to decision makers. One aspect that has come up in repeated studies is the requirement for telematics that acquire the fuel status of a vehicle and transmit it from the platform. The idea can be drawn from the successful use of telematics in industrial control systems. Field Management Units (FMU) acquire data from sensors and then transfer and load the data into logic controllers that automate functions in the system to regulate behavior.

The challenge is that the data acquisition devices, Automated Information Modules (AIMs), are not integrated into the design of the current fleet of tactical

vehicles. The MTVR does have a Controller Area Network (CAN) bus that collects telematics from the engine. An intermediate solution that is to use Commercial-Off-The-Shelf (COTS) technology to fill the gap.

FuelMaster is a vendor that already provides fuel accountability solutions to the Marine Corps and several defense labs joined to test the utility of their FMU mounted to an MTVR with a fuel pod. The FMU integrates with a hose system that measures flow and creates a data link with the AIM device on vehicles during retail distributions. The data acquired provides telematics information on the vehicle's health and performance since the last reading.

To utilize the data, the experiment incorporated a prototype of visualization software that extracts, loads, and transfers (ETL) the data into tables that can draw attention to high idle times, vehicles requiring maintenance, and an estimate of the fuel status and fuel efficiency of the vehicle during its mission. These experiments were still in proof-of-concept stages during the study, so there were not significant samples of data drawn to evaluate the utility of the data in a field setting.

b. Potential Benefits

Regardless, there are several other studies and initiatives that document the impact of fuel telematics along with considerations for the technology to be effective (Robison, 2015; Henton & Noack, 2015). One key component for successful implementation of vehicle health telematics is a logistics enterprise architecture, which has been designated as Global Combat Service Support (GCSS). The joint program directs services to develop information systems that ensure visibility of assets and their condition throughout the Defense Global Distribution Network (GDN).

The concepts shift data genesis, interpretation, and filtering from humans to machines. Humans would still play a role in determining thresholds and prioritizing support, but all of the demand and supply management functions would be automated. The goal is to illuminate data delays and minimize distortion to a level where it is negligible and commanders are able to maximize their operational reach with the assets available. So, the benefit of telematics is not directly in the value of the new data, but

how it is incorporated in resource decisions throughout the organization (Pedro-Dagoberto, 2013).

c. Technology Risks

However, like any information technology endeavor, the goals of the future system technologies face steep obstacles. The Marines are continuously training and operating real world missions with equipment that is worn from waging two wars over the last 15 years. The GCSS Marine Corps Enterprise Resource Planning (ERP) tool has been met with many cost and time overruns; which creates a requirement for commands to adopt more technologies to bridge legacy systems and middleware that may increase fragility in information systems.

Also, partial implementation of resource decision making policy in the tactical supply chain would undermine benefits (Pedro-Dagoberto, 2013). The reason being that optimized supply chain technologies require synchronization that behave like rowing crews in a way. If one node does not adjust according to the changes in demand at the retail end, the entire supply chain suffers from the disruption.

While the Marine Corps continues to win battles, E2C2S system development requires more clarity on what factors sensors should be focused on. The following section conducts quantitative analysis of the effects of fuel telematics and will attempt to provide insight on harmonizing the technology developments with changes in structure and policy to enable greater operational reach for the MAGTF.

B. QUANTITATIVE ANALYSIS

1. Introduction

In research and development, cost and schedule risks are common obstacles that threaten the success of a program. Computer simulations are useful tools to mitigate risks during technology maturation, as they quickly evaluate options without expending resources on physical options. Previous studies suggest that fleet telematics can unlock a competitive edge for business, but the caveat is that the data does not add value on its own. How data is incorporated into decision-making and acted on is a critical factor that

needs consideration in control system design and engineering (Robison, 2015). The following section establishes two simulation models: an As-Is and a To-Be that are based on the data from the qualitative analysis section.

The models are designed to simulate and reproduce symptoms of unstable supply chain dynamics, which are primarily characterized with stocks that exhibit behavior of oscillation with high amplitudes (Sterman, 2000). The problem with fuel consumption in the Marines is that commanders are unable to determine how their decisions are impacted by fuel. So, any deviation in consumption patterns creates situations of unforeseen high demand and situations where there is insufficient capacity to accept distributions.

The Beer Distribution Game inspired the idea of using simulation software to replicate these dynamics in a model of a tactical fuel supply chain. The modeling process steps include problem articulation, formulating a dynamic hypothesis, formulating a simulation model and testing (Sterman, 2000). The finding and conclusions will address the policy design, evaluation, and recommendations.

2. Problem Articulation

The problem is that dynamic demand creates the need for high inventory coverage of fuel for sustained tactical operations in the Marine Corps. The dynamic demand creates a high level of variance in unit fuel stocks and fuel distribution missions. This is a problem because the growth of fuel requirements has a positive relationship with the footprint of the MAGTF sustainment 'tail'. While fuel resupplies are in high amounts, distribution assets have low utilization rates. The result is a MAGTF with reduced operational reach and increased vulnerability by presenting adversaries with high-value targets in the form of large supply convoys.

The qualitative analysis suggests the root cause of the dynamic demand is poor demand side management decisions within supply nodes. A single node may operate efficient to local policy (see Figure 17), but in reality the node is subject to delays in information and fuel flows of interdependent loops that form the supply chain (see Figure 23). Delays cause a phase shift of demand and distribution responses, which leads to amplification of inventory corrections.

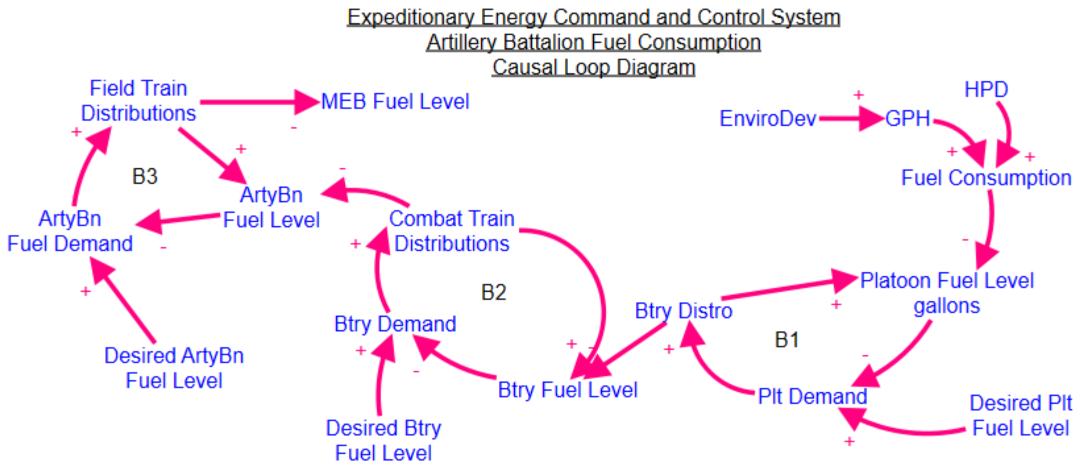

Figure 23. Causal Loop Diagram, High-Order Goal Seeking Fuel Supply and Demand.

The fuel supply chain (see Figure 23) is a cycle that flows fuel forward through distributions to reduce demands. The platoon activity at the right are the consumer or customers of the supply chain. The goal of the feedback loop (B1) is introduced as the Desired Plt Fuel Level; demand is the difference between the goal and perceived fuel level. There is a small delay, of 12–24 hours for the demand to form into an order for fuel. Orders are transformed into distributions by the next variable in the causal loop chain, which is the artillery battery for the platoon.

The staff functions and alignment create an iterative sequence of loops. Above the consumer is the retail supply activity or battery. The battery’s demands are satisfied by the combat trains that distribute from the battalion stocks (B2). The battalion and its combat trains function as a distributor. The distributor’s demands are met by the wholesaler through field trains (B3). The field trains draw fuel from the MEB stocks at the AAEFS. The MEB is designed to function for 30 days without external resupply; while they may have an external supply activity acting as the factory role, the study is focused on the dynamics within the MEB supply chain.

The causal loops are interdependent since the distributions at each level drive the goal seeking behavior in the level below, while the distributions simultaneous drive the stock at their respective level away from its goal, creating a demand. Accordingly, each

loop has counterbalancing processes that communicate supply and demand. The supply side management decisions involve the quantity and frequency of distributions and are constrained by the capacity and flow limits of each stock and flow. The demand side management decisions involve reporting demand and deciding how much to order.

3. Formulating a Dynamic Hypothesis

The independent variables must be within the control of the either the supply or demand side management decisions. The variables that have the highest potential increase operational reach are the inventory adjustment times and the inventory coverage. Information delays create phase shifts in demand and supply signals. These delays interact with inventory coverage goals by creating a perception of high error between the current state and the desired state of the inventory. The demand side decision is to increase demand without regard to the fuel already being loaded and transferred in a distribution mission via a supply train (see Table 2).

Table 2. Relationship Between Information Delay & Inventory Coverage on Operational Reach.

	High inventory coverage Desired stock => 2 DOS	Low inventory coverage Desired stock < 2 DOS
High information delay Time delay => 1.0 days	High oscillation/ no operational impact	High oscillation/ high operational impact
Low information delay Time delay = 0.0 days	Low oscillation/ no operational impact	Low oscillation/ low operational impact

Oscillations are symptomatic of goal seeking systems with information delays. The behavior of the stocks in the system can reveal the elasticity or resilience the system has to a perturbation. A perturbation would be any change from a state of equilibrium. The system’s ability to approach equilibrium (achieve the goal) can be measured by the amplitude of the phase shift on subsequent stocks as well as the time it takes for the system to recover equilibrium (Sterman, 2000; Abdel-Hamid, personal communication, February 29, 2016).

4. Formulating a Simulation Model

The model of the fuel supply chain has two categories; the flow path of the fuel and the flow path of the demand. To create a controlled experiment, certain assumptions must be made to reduce noise or extraneous factors to variables being tested. Several assumptions were adopted for the model (see Table 3).

Table 3. Modeling Assumptions.

Stock and flows are unidirectional
Stocks are nonnegative
Distribution capacities are unlimited
Every source of demand belongs to a single platoon/battery/battalion/regiment/MEB
Distributions at the platoon level are instantaneous (loop omitted)
Orders originate and close at the battery/company level
Simulation takes place within the MEBs 30 day design
Demand and supply flow is stable (deterministic)
Fuel distributions are discrete events.
Model is specified to run over 30 Days with 0.5 step increments
Stock unit of measure is Gallons

The building blocks of a supply chain are goal-seeking loops that balance the acquisition and loss rate of a stock. The basic model of a fuel stock and flow was built and tested in equilibrium. Once this was achieved, a discrete conveyor was added to represent the distribution delay in the supply line. Conveyors carry a stock between processes and these were set with a transit time of one day and constrained to the stock limit at the receiving end. Additionally, a delay was formed to represent the average day it takes for demand to be converted into an order between the desired arrival rate and order rate at the left side of variables.

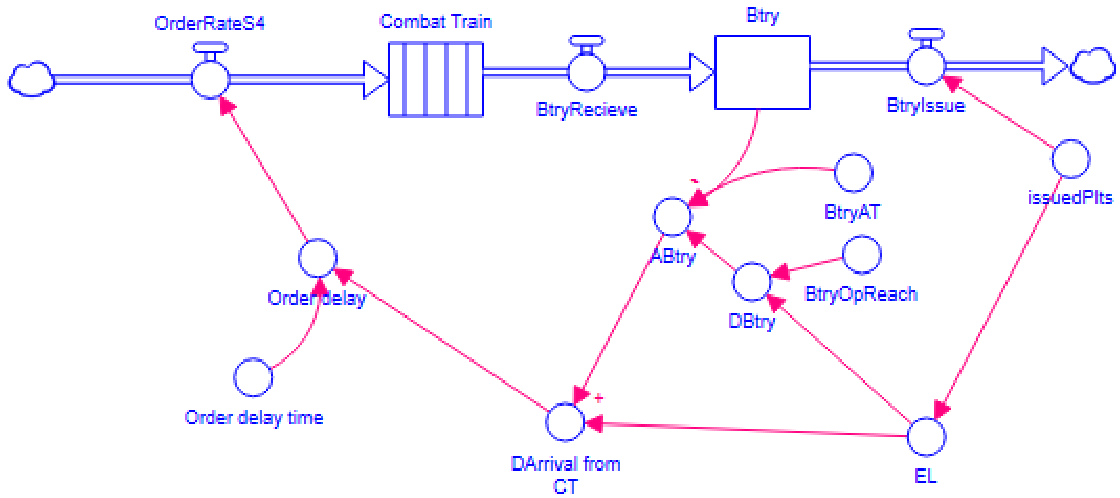

Figure 24. Second-Order Supply System with Distribution and Delay. Adapted from Sterman (2000).

The retail level of the supply chain (see Figure 24) is represented by the artillery battery stock and flows. The stock is equal to the integral of the receive and issue rates. The variable is initialized to equal the initial battery issue at time (0) and the unit of measure is gallons. The modeling software automatically makes the unit of measure at the flows Gallons/Days, which drives the units of measure for the proceeding formulations.

$$Btry = \int (BtryIssue - BtryRecieve)$$

The demand signal originates with the distributions to the platoons. These are represented as the exogenous variable *issuedPlts*. In equilibrium, this variable is equal to 9,600 Gallons. To perturb the system from equilibrium, the following formulation was used.

$$issuedPlts = 9600 - STEP(600, 5)$$

Similar to the Beer Distribution Game, the perturbation on the system is a single impulse on the fifth day where demand drops down from the assault rate to the sustained rate (Chiarotti, 2007). The issue rate is equal to the *issuedPlts* variable. The demand is then fed into *expected loss* (EL), which is the forecasting technique that averages the previous three days' demands.

$$EL = SMTH1(issuedPlts, 3)$$

The output is the expected losses for the day in gallons. The demand then goes through an inventory correction policy. The desired inventory coverage is the number of days the stock must have as a buffer against dynamic demand. This is the battery's operational reach (BtryOpReach), for the purpose of this model, it was initialized at three days. The expected loss is then multiplied by the inventory coverage to form the *desired battery stock level* (DBtry).

DBtry = EL * BtryOpReach

The inventory adjustment (ABtry) is the difference between the desired and battery stock averaged by the battery stock adjustment time (BtryAT).

ABtry = (DBtry - Btry)/BtryAT

The gallons/days are then added to the expected loss to form the *desired arrival rate* (DArrival from CT). At this point in the process, the demand has reached the transition point where it becomes an order in the system. This is accomplished by applying a delay before it is submitted to the battalion logistics section (OrderRateS4) for fulfillment.

Order delay = DELAY(DArrival from CT, 1.0)

Once the order hits the logistics section it is fulfilled in the next day's battalion combat train, which sustains the battery positions. For the purpose of this simulation, the battery can accept up to 18,000 gallons in a shipment and is assumed to not have a capacity limit.

The supply chain replicates its structure and behavior at the artillery battalion, which represents the distributor. The difference with the battalion is that it is sustained by field trains, which draw fuel from the Marine Expeditionary Brigade (MEB) stocks and carry them forward to the supported battalions. The MEB stock represents the wholesaler and for the purpose of the tactical scenario, the theater source (factory) is omitted since the problem is focused on the 30-day organic stocks carried by the MEB.

To formulate the To-Be model, the desired arrival rate from the combat trains has no delay. This represents the autonomous flow of demand gained with telematics. Also, the To-Be model assumes a near-real time sharing of consumption data within the MEB.

Accordingly, the stock adjustments from the battery level are summed into the stock adjustments of all nodes up the fuel chain for their next distribution.

5. Testing

Once the As-Is and To-Be models were calibrated, a 30-day simulation was ran with identical variable settings, the To-Be model having zero delays.

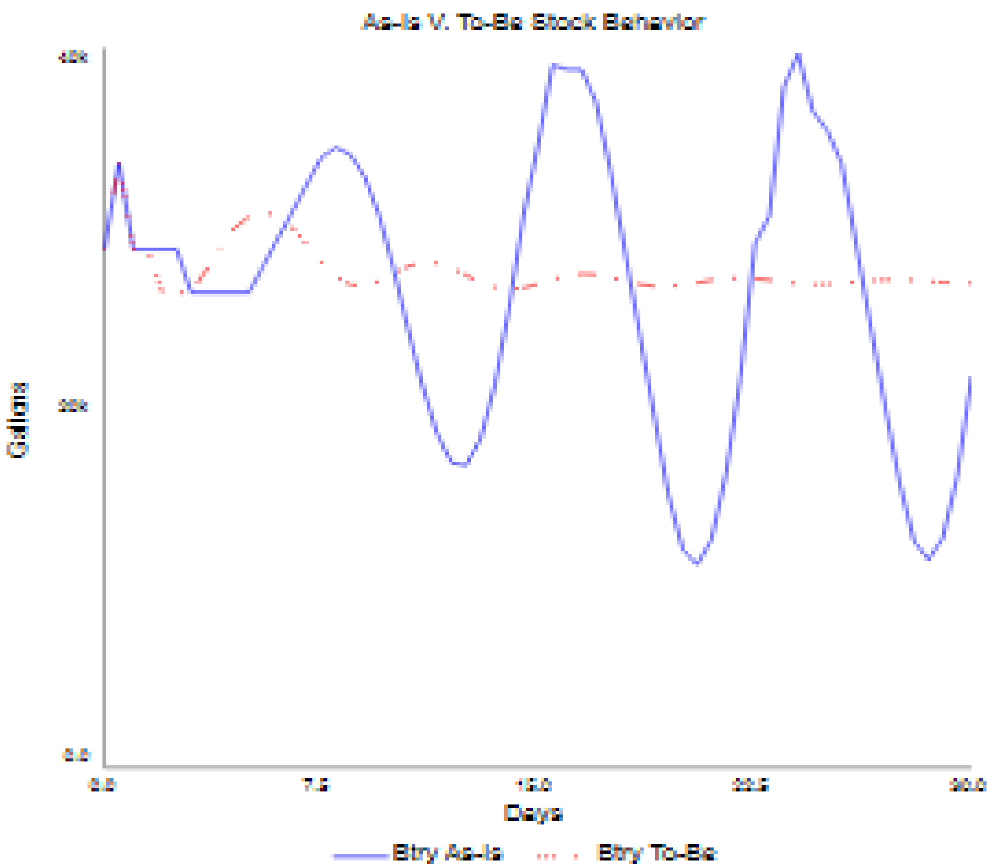

Figure 25. As-Is Versus To-Be Stock Behavior.

The battery-level stock behavior of the As-Is versus To-Be systems (see Figure 25) are shown relative to each other. The battery oscillations increase in amplitude throughout the 30-day period, ranging between 15k - 40k gallons. The To-Be model oscillations show signs of damping and approach equilibrium after the 13th day.

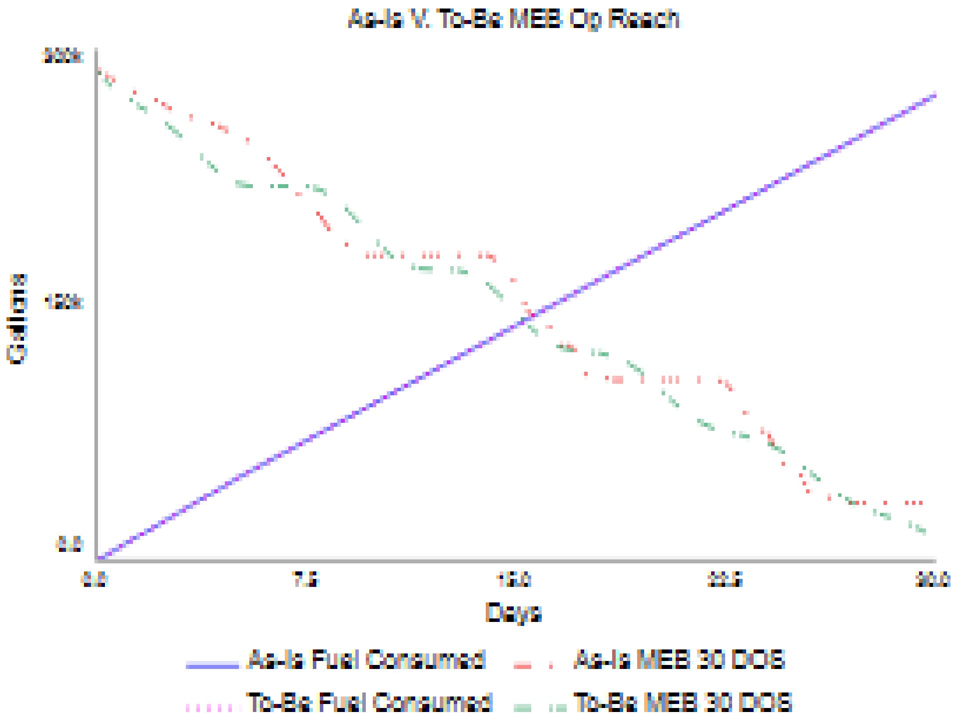

Figure 26. As-Is Versus To-Be MEB Stock Behavior.

Both models were initialized with a 30-day supply of fuel for the battery at the assault rate. Consumption for both models was linear while the MEB stock showed oscillation as it was nearly depleted at the end of the period. The As-Is model stocks finished at 36k gallons while the To-Be model was down to 14k gallons (see Figure 26).

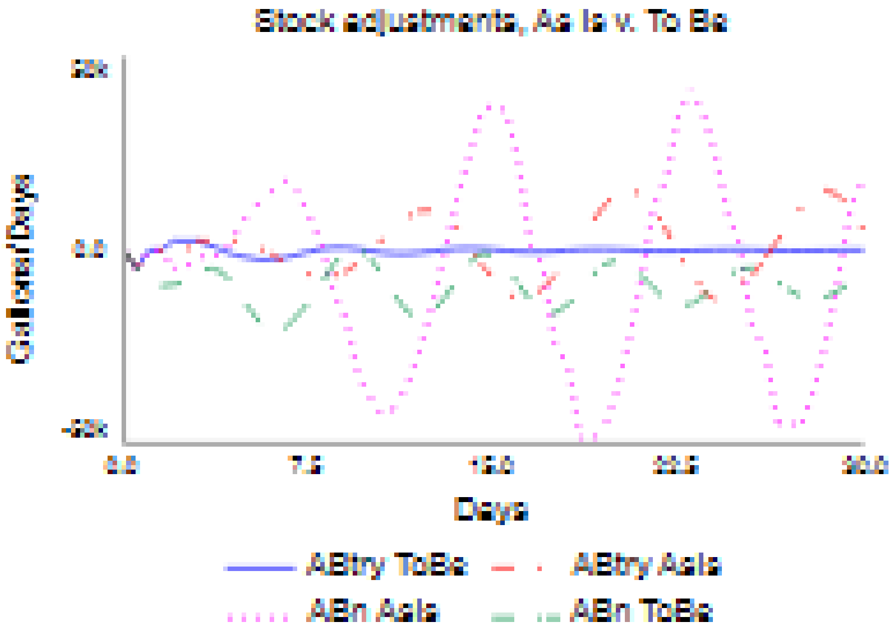

Figure 27. As-Is Versus To-Be stock Adjustments at Battalion and Battery-Level.

The stock adjustments are calculated at each step increment, which would be twice a day. This is consistent reporting behavior observed in a field environment. The As-Is adjustments reflect the same behavior mode as the stock behavior (see Figure 27). Negative values for adjustments are explained by surpluses in the stock, or when the stock exceeds the desired stock amount.

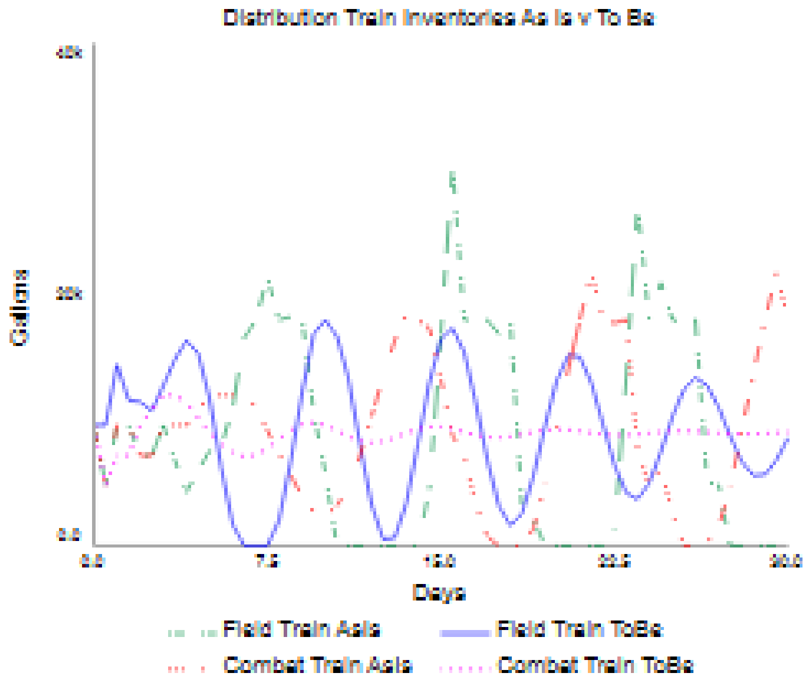

Figure 28. As Is Versus To-Be Conveyor Stocks.

The conveyors acted at the distribution convoys in the tactical fuel supply chain. These exhibited the same mode of behavior as the stocks in the As-Is and To-Be systems (see Figure 28). Conveyors are a type of stock; in this model, they are non-negative as surpluses are not carried back up the supply chain. A zero stock represents a step where there is no fuel taken from the supply node down to the next node in the supply chain.

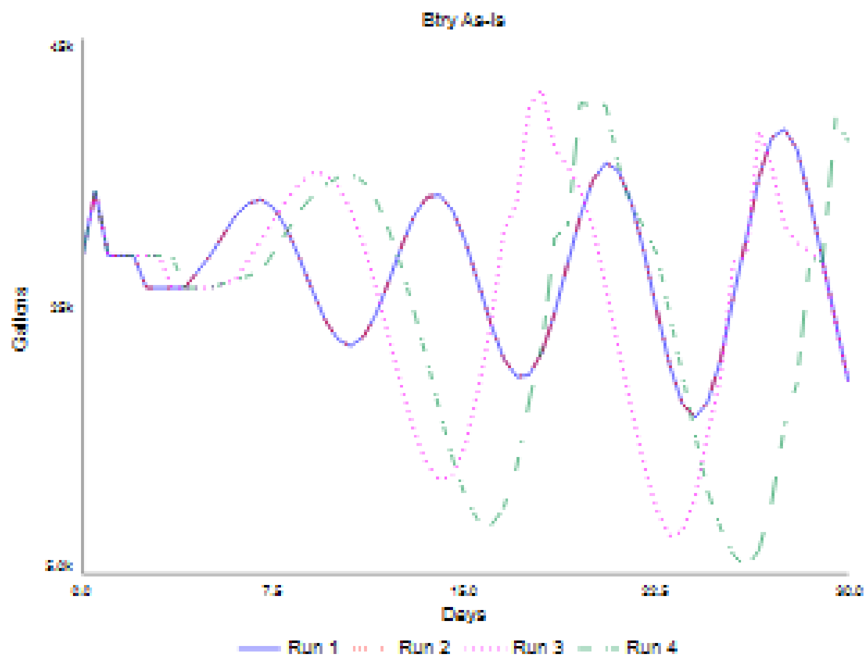

Figure 29. Sensitivity of Battery Stock to Information Delay, As Is Model.

The sensitivity analysis was conducted in two trials observing the battery and battalion stocks for the As-Is model. The order delay parameter was incrementally varied from 0.0-2.0 in 0.5 steps (see Figures 29 and 30). Of note, stocks were initialized at 28.8k gallons (or 3 DOS) and conveyors were initialized at 9,600 gallons.

It is apparent in the sensitivity analysis that the information and supply delays at the battery-level created a "bullwhip" effect on the oscillations at the battalion-level. As delays increase, the phase shift to the right is apparent and the amplitudes at the battalion level show exponential or compounded growth with each increase of delay greater than 0.5 Days. While these findings are consistent with the reported dysfunctional symptoms of tactical supply chain, it is important to note that the experiment purposely controlled for exogenous variables. There is no weather, randomness, or other logistics factors acting on the supply system; yet, the As-Is model behaved in an unstable manner. The following chapter will dig deeper into the implications of this for military supply systems along with recommendations for the implementation of data acquisition technologies (telematics).

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V. RESULTS AND CONCLUSIONS

A. EXPERIMENTAL RESULTS

1. Hypothesis Testing

The hypothesis testing found that the As-Is model, with high information delay and high inventory coverage, did exhibit greater amplitude of oscillation than the To-Be model. When inventory coverage was less than three days for the battalion, operational reach was disrupted despite the MEB still having an ample stock. The behavior is a result of instability of the system. Even with a relatively small perturbation, a 7% decrease in demand, the As-Is system battalion stocks were depleted in the sensitivity analysis when the delay was greater than or equal to 1.5 days.

The low information delay on the As-Is model allowed for a 0.95 DOS coverage at the battery and 2.8 DOS coverage at the battalion without stocks being depleted. So, the battery did perform better than expected in the As-Is model.

The stability of the To-Be system was observed to be nominally resilient as it was able to achieve 95% equilibrium at the battery by day 13. The As-Is system showed increasing instability up to the 30-day mark. The peak amplitude of the battery reached 28k gallons, while the battalion peaked at 48k gallons. The As-Is battery peaked at 36k gallons and the battalion peaked 62k gallons. The 171% amplification in the To-Be and 172% amplification in the As-Is models are consistent with expectations based on previous supply chain dynamic cases

The sensitivity analysis on time delay with the As-Is model demonstrated that increasing the delay had a positive effect on amplification, making the model less stable. One notable observation was that in the As-Is model, the battalion had low impact to operations only when information delay was zero, otherwise there were periods of high operational impact.

2. Potential Impact on Operational Reach

The operational reach of the MEB is decreased with fully implemented telematics; based on the As-Is system finishing the model with 21k gallons more than the To-Be model. While this was an unexpected result, exploration of parameters provided some insight on how these findings can be explained by the assumptions of the model. First, the model assumed distribution capacities equaled the capacity of the units–meaning that sustainment trains (conveyors) could always fulfill demand and the battalion could receive this fuel as it arrived. Looking at the operational tempo in the As-Is model, the field trains would deliver 21k gallons and the following mission was eight days later at 30k gallons. To put it in perspective, the same demand signal was answered in the To-Be model with a 16k gallon delivery with a two-day pause before an 18k gallon delivery.

The As-Is model is able to extend its operational reach further in time than the To-Be model because it is working harder with a lower utilization rate on the equipment. This resulted in oscillations that led to As-Is model periods where more fuel was reserved in the supply line. The reality is that field trains would struggle to lift the 30k gallons in a day and would most likely create a backlog or have to double mission rate, which would double the cost of delivering fuel that day. The second-order effect would be that the battalion and battery would have to increase their inventory coverage to compensate for the increased delays, which would create a reinforcing feedback loop that exponentially created higher demands on the field trains.

The To-Be model is a more resilient system that shows very little risk to operations based on fuel consumption. This potentially increases operational tempo and advantage against adversaries. The To-Be model finished the 30 days with 13k gallons and the As-Is model finished with 34k gallons. However, the telematics are useful beyond synchronizing the inventory adjustments along the supply chain. If commanders are able to improve fuel efficiency by 7% across the vehicle in the MEB, they would finish the simulation with 36k gallons.

B. LIMITATIONS

The simulation was limited in its approximation of reality. This was intentional, but it is noted that a more accurate simulator would behave as a micro-world – accurately capturing consumption variance, weather, load configurations, and other logistics considerations. Also, the technology theorized in the model are more mature than the architecture being prototyped at the time of this study. Therefore, adoption of telematics would require further development.

C. RECOMMENDATIONS

1. Material and Non-Material Solutions

With regard to operational reach, the findings of this study suggest very limited benefits for the Marine Corps through implementing telematics. Telematics that are fully integrated into the vehicle fleet will likely lead to increased operational tempo and more reliable supply lines—which will most likely increase fuel consumption activities. Telematics will give logisticians and commanders better visibility of their energy performance, but there is no evidence of a causal factor that would lead to decreased consumption in combat unless information was used to restrict maneuver or limit the advance of forward troops.

Demand signals acquired via telematics will require an overhaul of how supply and demand side management are executed in a tactical environment. Right now, Marines schedule a resupply push or they pull it on demand. Both scenarios use delayed and distorted data and result in unstable supply chain behavior. With increased automation and process re-engineering, data for all classes of supply should be entering the system with more velocity. Stock adjustments should be automated with human intervention minimized.

On the other hand, the advantages in the To-Be model suggest higher utilization of distribution assets that require lower lift capacity. This does suggest that “tail” or logistics footprint of the MAGTF can be leaned or reduced if amplitude maxima is reduced for lift requirements. Also, the company and higher echelon units are able to operate with smaller inventory coverage; even if they are disrupted due to exogenous

factors, the To-Be system's behavior mode has a better ability to rapidly absorb changes in demand.

While emergency resupply capacity is a must in combat, humans are victims of bounded rationality when it comes to managing supply chains as separate nodes. People tend to make sound decisions with the information they have at hand, at the expense of the system outside their purview (Sterman, 2000). To create a hierarchy that collaborates over adjustments would increase process layers and complexity.

To counter the organizational resistance in the supply and distribution occupation fields, the Marine Corps should invigorate the entry and intermediate-level formal schools with the lessons learned about supply chains. While many Marines are quick to point at bad reporting, weather, or uncertainty as root causes for dysfunction, it is more likely that it is the structure and design of the resource decisions within that create systemic dysfunction. Also, commercial off the shelf solutions need to measure for alignment and fit into current processes. The more the organization needs to change to fit a technology they had no hand in developing, there may be a greater risk for low adoption rates.

2. Focus Data Aggregation on Bottom-up Approach

Effects of distortion were omitted from the design of the simulation. This is because distortions from data transformations, translations, and error are all noise in the information system. While decision makers may prefer dealing with DOS to dealing with gallons, data should never be propagated as a less accurate approximation. The best quality sensor data should always be propagated forward with as much integrity to its origin as possible. This makes aggregations more resilient to error propagation.

The principle of timing in computer science is an excellent example. The system clock in the core of a computer does not keep time by Gregorian or any other calendar. The time is kept as a continuous interval with 100-nanosecond steps from epoch on 1 January 1970 00:00:00. Whenever a user sees a date, that is an abstraction converted by a higher level of the operating system. By keeping the kernel data as an interval,

bookkeeping is made computationally trivial when it comes to adjusting, comparing, and computing time.

Until sensors and computers totally automate stock management, Marines should focus on finding safe tactics, techniques, and procedures for measuring bulk fluids. The success of telematics in the vehicle fleet are interdependent with the data quality and resource decisions made with regards to intermediate storage.

D. FUTURE STUDIES

1. Field Experiment to Measure Cognitive Loads to Assess Return on Knowledge

With the push to control dynamic supply chains, there will be a need for increased automation, process improvement, and re-engineering. Some developments may find opportunities to gain benefits by shifting workload onto customer units; roles being discussed include drivers, platoon commanders, and logistics specialists. In order to measure the return on investment, there needs to be an understanding of the current and future cognitive loads carried by these actors. These efforts may benefit from a study that surveys both customer and supply support roles along with leaders of these units to get a better understanding of the cognitive loads associated with target processes.

2. Field Experiment to Measure Information Distortion in Fuel Performance

While this study collected qualitative data on information distortion in fuel performance processes, a quantitative would provide a better approximation of the impact on resource decisions. It is possible that the distortions have a negligible effect when compared to the time delays and changing the color-coded reporting may increase supply chain dysfunctions.

3. User-based Collaborative Design of User Interfaces for E2C2S

The users who will be in the occupation fields charged with executing Expeditionary Energy Command and Control should be included in the development of user interfaces with resource decision system. The inclusion of users early on may

increase the chances of success implementation and improve adoption rates within the organization.

4. Case Study of Information System Maturity Model for Combat

As the battle concepts in the military become more computerized, the operational plans are updated to reflect capabilities advertised by the combat developers. While technology has evolved, combat still drags units into the age of manual and analog protocols on a regular basis. Additionally, the U. S. faces non-conventional cyber-threats. This reaffirms that there is no single military information system. The information system is constantly in flux as it relates to technology and organizational maturity. The military services are in need of an Information System Maturity Model for Combat. While Marine Corps telecommunications have standards for establishing services by time, when and how automated information systems are introduced on the battlefield are not widely discussed. A model may help in guiding operational concepts, training, and development of technology performance parameters in the future.

E. CONCLUSION

The Marine Corps has an opportunity to engineer near-real-time consumption data into every node of the tactical supply chain. This new concept of total demand visibility is alluring for the potential benefits that can be achieved with optimized tactical supply chains. While operational tempo, agility, and supply chain stability may improve; there is little evidence that fuel data will extend operational reach if its implantation is limited to resource decisions within the supply chain. Combat units must find ways to identify waste or other opportunities to reduce footprint using analytical potential that emerges when information delays are eliminated and telematics perform data acquisition for the information system.

APPENDIX. A. SIMULATION DATA

Table 4. Stock Data.

Days	As-Is Fuel Consumed	To-Be Fuel Consumed	As-Is MEB 30 DOS	To-Be MEB 30 DOS	Bn AsIs	Bn ToBe	Btry As-Is	Btry To-Be
0	0	0	288000	288000	28800	28800	28800	28800
1	9600	9600	278400	273600	28800	31200	28800	28800
2	19200	19200	271200	262133	31200	36000	28800	26400
3	28800	28800	261600	249370	28800	35467	26400	26400
4	38400	38400	257333	233007	28800	36830	26400	28800
5	48000	48000	249770	221277	21067	44193	26400	30600
6	57000	57000	238785	219598	16630	48473	29400	30600
7	66000	66000	220785	219598	16565	42925	32400	29050
8	75000	75000	202785	217591	27187	34430	34450	27278
9	84000	84000	184785	205379	41276	26755	32828	26772
10	93000	93000	178988	187379	56806	29358	27739	27454
11	102000	102000	178988	174055	57858	38654	21209	28062
12	111000	111000	178988	170785	47580	43777	16953	27767
13	120000	120000	178988	170167	31225	38444	18232	26968
14	129000	129000	178988	162044	13225	29766	25587	26571
15	138000	138000	162141	145573	0	28418	34587	26867
16	147000	147000	144141	130149	9672	35828	38812	27338
17	156000	156000	126141	123283	26934	42599	36986	27399
18	165000	165000	108141	121664	44934	40763	28724	27052
19	174000	174000	106115	116070	61534	33322	19724	26754
20	183000	183000	106115	102906	54015	29650	12125	26814
21	192000	192000	106115	87857	36015	33683	12670	27081
22	201000	201000	106115	78155	18015	39855	21670	27211
23	210000	210000	92840	73931	15	40745	30670	27088
24	219000	219000	74840	68948	8551	36003	39670	26899
25	228000	228000	56840	58677	23885	31862	35409	26866
26	237000	237000	38840	45308	41885	33024	29076	26990
27	246000	246000	33984	34288	58376	37416	20076	27100
28	255000	255000	33984	27582	54055	39537	12585	27077
29	264000	264000	33984	21923	36055	37295	12760	26975
Final	273000	273000	33984	13340	18055	33909	21760	26924

Table 5. Flow Data

Days	BnRecieve AsIs	BnRecieve ToBe	BtryIssue AsIs	BtryIssueToBe	BtryRecieve AsIs	BtryRecieve ToBe	Order RateCLB AsIs	OrderRateCLB ToBe	OrderRate S4 AsIs	OrderRateS4 ToBe
0	19200	19200	9600	9600	19200	19200	9600	19200	9600	9600
1	9600	19200	9600	9600	9600	9600	9600	13600	9600	9600
2	9600	13600	9600	9600	9600	9600	9600	12178	9600	12000
3	9600	12178	9600	9600	9600	12000	4000	16323	9600	12000
4	4000	16323	9600	9600	9600	12000	7378	14269	12000	9600
5	7378	14269	9000	9000	12000	9600	8057	3359	12000	7800
6	8057	3359	9000	9000	12000	7800	19195	0	12000	7067
7	19195	0	9000	9000	12000	7067	25997	0	8267	8107
8	25997	0	9000	9000	8267	8107	26436	9353	4757	9526
9	26436	9353	9000	9000	4757	9526	11593	18672	2354	9786
10	11593	18672	9000	9000	2354	9786	0	16049	3730	8933
11	0	16049	9000	9000	3730	8933	0	5496	8649	8207
12	0	5496	9000	9000	8649	8207	0	0	15060	8420
13	0	0	9000	9000	15060	8420	0	5547	19234	9162
14	0	5547	9000	9000	19234	9162	8978	15316	17898	9519
15	8978	15316	9000	9000	17898	9519	36000	17046	8978	9196
16	36000	17046	9000	9000	8978	9196	36000	9122	1476	8705
17	36000	9122	9000	9000	1476	8705	33768	1772	0	8631
18	33768	1772	9000	9000	0	8631	4052	3670	0	8969
19	4052	3670	9000	9000	0	8969	0	11649	7297	9261
20	0	11649	9000	9000	7297	9261	0	15673	16290	9196
21	0	15673	9000	9000	16290	9196	0	11483	23885	8926
22	0	11483	9000	9000	23885	8926	2557	4949	23337	8794
23	2557	4949	9000	9000	23337	8794	30117	3949	2587	8916
24	30117	3949	9000	9000	2587	8916	36000	8912	5334	9103
25	36000	8912	9000	9000	5334	9103	35558	13296	0	9135
26	35558	13296	9000	9000	0	9135	9710	12134	593	9011
27	9710	12134	9000	9000	593	9011	0	7556	6925	8901
28	0	7556	9000	9000	6925	8901	0	5311	15925	8924
29	0	5311	9000	9000	15925	8924	0	7618	23416	9025
Final										

Table 6. Inventory Adjustment Data.

Days	DArrival from CT AsIs	DArrival from CT ToBe	DArrival from FT AsIs	DArrival from FT ToBe	Combat Train AsIs	Combat Train ToBe	Field Train AsIs	Field Train ToBe	issuedPlts AsIs	issuedPlts ToBe
0	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600
1	9600	9600	9600	4000	9600	7200	9600	14400	9600	9600
2	9600	12000	4000	178	7200	9600	7200	11467	9600	9600
3	12000	12000	7378	4323	9600	12000	9600	12763	9600	9600
4	12000	9600	8057	4669	9600	11400	4267	16363	9600	9600
5	12000	7800	19195	-4441	12000	9000	7563	11730	9000	9000
6	8267	7067	25997	-11801	12000	7450	10985	1680	9000	9000
7	4757	8107	26436	-8606	11050	7228	18000	0	9000	9000
8	2354	9526	11593	-173	7378	8494	18000	2007	9000	9000
9	3730	9786	-9659	8886	3911	9682	18000	12211	9000	9000
10	8649	8933	-31818	7116	2470	9608	5797	18000	9000	9000
11	15060	8207	-34594	-2711	4745	8705	0	13324	9000	9000
12	19234	8420	-18681	-8794	10278	8201	0	3270	9000	9000
13	17898	9162	8978	-3615	16355	8603	0	618	9000	9000
14	10503	9519	36556	5797	18000	9296	0	8123	9000	9000
15	1476	9196	50215	7850	13225	9471	16847	16471	9000	9000
16	-2768	8705	33768	417	7175	9061	18000	15424	9000	9000
17	-956	8631	4052	-6859	738	8653	18000	6866	9000	9000
18	7297	8969	-23416	-5299	0	8702	18000	1619	9000	9000
19	16290	9261	-44723	2388	1400	9060	2026	5594	9000	9000
20	23885	9196	-30425	6476	9545	9267	0	13164	9000	9000
21	23337	8926	2557	2556	18000	9130	0	15049	9000	9000
22	14335	8794	30117	-3845	18000	8877	0	9702	9000	9000
23	5334	8916	54817	-4966	18000	8812	13276	4225	9000	9000
24	-3667	9103	35558	-191	4739	8967	18000	4983	9000	9000
25	593	9135	9710	4161	2667	9124	18000	10271	9000	9000
26	6925	9011	-18555	3123	0	9109	18000	13369	9000	9000
27	15925	8901	-40228	-1346	1509	8977	4855	11020	9000	9000
28	23416	8924	-29989	-3613	9175	8898	0	6706	9000	9000
29	23240	9025	2888	-1407	18000	8949	0	5658	9000	9000
Final	14240	9077	30387	2069	18000	9044	0	8583	9000	9000

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APPENDIX B. SIMULATION MODEL DIAGRAM

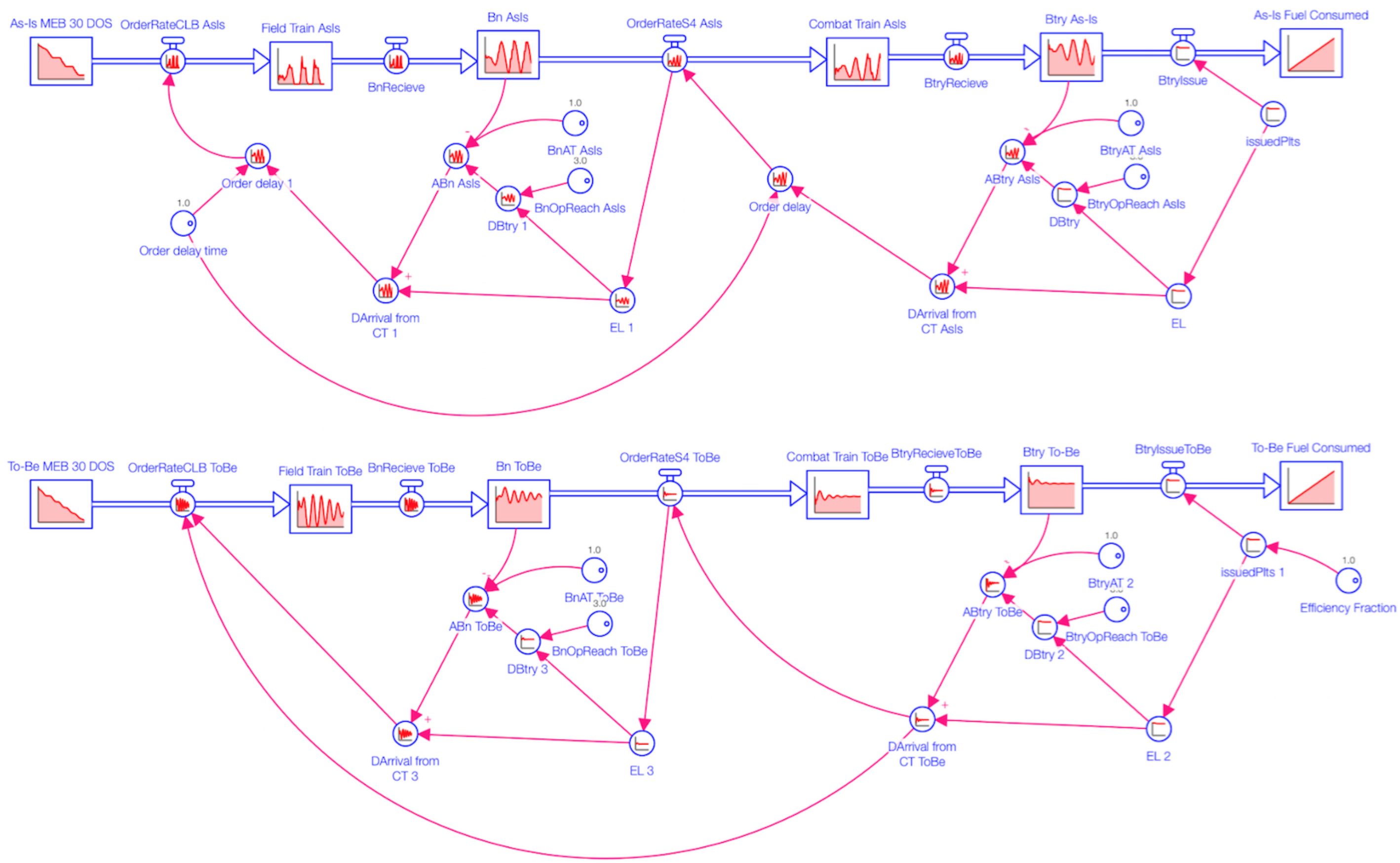

Figure 30. As-Is and To-Be Simulation Design

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APPENDIX C. XMILE SIMULATION MODEL FORMULATION

Top-Level Model:
“As-Is_Fuel_Consumed”(t) = “As-Is_Fuel_Consumed”(t - dt) + (BtryIssue_AsIs) * dt
INIT “As-Is_Fuel_Consumed” = 0
INFLOWS:
BtryIssue_AsIs = issuedPlts_AsIs
“As-Is_MEB_30_DOS”(t) = “As-Is_MEB_30_DOS”(t - dt) + (- OrderRateCLB_AsIs) * dt
INIT “As-Is_MEB_30_DOS” = 9600*30
OUTFLOWS:
OrderRateCLB_AsIs = Order_delay_CLB
Bn_AsIs(t) = Bn_AsIs(t - dt) + (BnRecieve_AsIs - OrderRateS4_AsIs) * dt
INIT Bn_AsIs = DBn_AsIs
INFLOWS:
BnRecieve_AsIs = CONVEYOR OUTFLOW
OUTFLOWS:
OrderRateS4_AsIs = Order_delay_Bn
Bn_ToBe(t) = Bn_ToBe(t - dt) + (BnRecieve_ToBe - OrderRateS4_ToBe) * dt
INIT Bn_ToBe = DBn_ToBe
INFLOWS:
BnRecieve_ToBe = CONVEYOR OUTFLOW
OUTFLOWS:
OrderRateS4_ToBe = DArrival_from_CT_ToBe
“Btry_As-Is”(t) = “Btry_As-Is”(t - dt) + (BtryRecieve_AsIs - BtryIssue_AsIs) * dt
INIT “Btry_As-Is” = DBtry_AsIs
INFLOWS:
BtryRecieve_AsIs = CONVEYOR OUTFLOW
OUTFLOWS:
BtryIssue_AsIs = issuedPlts_AsIs
“Btry_To-Be”(t) = “Btry_To-Be”(t - dt) + (BtryRecieveToBe - BtryIssueToBe) * dt
INIT “Btry_To-Be” = DBtry_ToBe
INFLOWS:
BtryRecieveToBe = CONVEYOR OUTFLOW
OUTFLOWS:
BtryIssueToBe = issuedPlts_ToBe
Combat_Train_AsIs(t) = Combat_Train_AsIs(t - dt) + (OrderRateS4_AsIs - BtryRecieve_AsIs) * dt
INIT Combat_Train_AsIs = 9600
TRANSIT TIME = 1
CAPACITY = INF
INFLOW LIMIT = 18000
INFLOWS:
OrderRateS4_AsIs = Order_delay_Bn

OUTFLOWS:
BtryRecieve_AsIs = CONVEYOR OUTFLOW
Combat_Train_ToBe(t) = Combat_Train_ToBe(t - dt) + (OrderRateS4_ToBe - BtryRecieveToBe) * dt
INIT Combat_Train_ToBe = 9600
TRANSIT TIME = 1
CAPACITY = INF
INFLOW LIMIT = 18000
INFLOWS:
OrderRateS4_ToBe = DArrival_from_CT_ToBe
OUTFLOWS:
BtryRecieveToBe = CONVEYOR OUTFLOW
Field_Train_AsIs(t) = Field_Train_AsIs(t - dt) + (OrderRateCLB_AsIs - BnRecieve_AsIs) * dt
INIT Field_Train_AsIs = 9600
TRANSIT TIME = 1
CAPACITY = INF
INFLOW LIMIT = 18000
INFLOWS:
OrderRateCLB_AsIs = Order_delay_CLB
OUTFLOWS:
BnRecieve_AsIs = CONVEYOR OUTFLOW
Field_Train_ToBe(t) = Field_Train_ToBe(t - dt) + (OrderRateCLB_ToBe - BnRecieve_ToBe) * dt
INIT Field_Train_ToBe = 9600
TRANSIT TIME = 1
CAPACITY = INF
INFLOW LIMIT = 18000
INFLOWS:
OrderRateCLB_ToBe = DArrival_from_CT_ToBe+DArrival_from_FT_ToBe
OUTFLOWS:
BnRecieve_ToBe = CONVEYOR OUTFLOW
“To-Be_Fuel_Consumed”(t) = “To-Be_Fuel_Consumed”(t - dt) + (BtryIssueToBe) * dt
INIT “To-Be_Fuel_Consumed” = 0
INFLOWS:
BtryIssueToBe = issuedPlts_ToBe
“To-Be_MEB_30_DOS”(t) = “To-Be_MEB_30_DOS”(t - dt) + (- OrderRateCLB_ToBe) * dt
INIT “To-Be_MEB_30_DOS” = 9600*30
OUTFLOWS:
OrderRateCLB_ToBe = DArrival_from_CT_ToBe+DArrival_from_FT_ToBe
ABn_AsIs = (DBn_AsIs-Bn_AsIs)/BnAT_AsIs
ABn_ToBe = (DBn_ToBe-Bn_ToBe)/BnAT_ToBe
ABtry_AsIs = (DBtry_AsIs-”Btry_As-Is”)/BtryAT_AsIs
ABtry_ToBe = (DBtry_ToBe-”Btry_To-Be”)/BtryAT_ToBe

BnAT_AsIs = 1
BnAT_ToBe = 1
BnOpReach_AsIs = 3
BnOpReach_ToBe = 3
BtryAT_AsIs = 1
BtryAT_ToBe = 1
BtryOpReach_AsIs = 3
BtryOpReach_ToBe = 3
DArrival_from_CT_AsIs = EL_Btry_AsIs+ABtry_AsIs
DArrival_from_CT_ToBe = EL_Btry_ToBe+ABtry_ToBe
DArrival_from_FT_AsIs = EL_Bn_AsIs+ABn_AsIs
DArrival_from_FT_ToBe = EL_Bn_ToBe+ABn_ToBe
DBn_AsIs = EL_Bn_AsIs*BnOpReach_AsIs
DBn_ToBe = EL_Bn_ToBe*BnOpReach_ToBe
DBtry_AsIs = EL_Btry_AsIs*BtryOpReach_AsIs
DBtry_ToBe = EL_Btry_ToBe*BtryOpReach_ToBe
EL_Bn_AsIs = SMTH1(OrderRateS4_AsIs, 3)
EL_Bn_ToBe = SMTH1(OrderRateS4_ToBe, 3)
EL_Btry_AsIs = SMTH1(issuedPlts_AsIs, 3)
EL_Btry_ToBe = SMTH1(issuedPlts_ToBe, 3)
issuedPlts_AsIs = 9600-STEP(600, 5)
issuedPlts_ToBe = 9600-STEP(600, 5)
Order_delay_Bn = DELAY(DArrival_from_CT_AsIs, Order_delay_time)
Order_delay_CLB = DELAY(DArrival_from_FT_AsIs, Order_delay_time)
Order_delay_time = 1

First_Order_Supply_Node:
S(t) = S(t - dt) + (AR - LR) * dt
INIT S = DS
INFLOWS:
AR = DAR
OUTFLOWS:
LR = O
AS = (DS-S)/S_AdjTm
CS = 3
DAR = EL+AS
DS = EL*CS
EL = SMTH1(O, 4)
O = 9600 - STEP(600, 4) + STEP(600, 5)
S_AdjTm = 4

Second_Order_Supply_Node_with_Distribution_and_Delay:
Btry(t) = Btry(t - dt) + (BtryRecieve - BtryIssue) * dt
INIT Btry = DBtry
INFLOWS:

```
BtryRecieve = CONVEYOR OUTFLOW
OUTFLOWS:
BtryIssue = issuedPlts
Combat_Train(t) = Combat_Train(t - dt) + (OrderRateS4 - BtryRecieve) * dt
INIT Combat_Train = 9600
TRANSIT TIME = 1
CAPACITY = INF
INFLOW LIMIT = 18000
INFLOWS:
OrderRateS4 = Order_delay
OUTFLOWS:
BtryRecieve = CONVEYOR OUTFLOW
ABtry = (DBtry-Btry)/BtryAT
BtryAT = 1
BtryOpReach = 3
DArrival_from_CT = EL+ABtry
DBtry = EL*BtryOpReach
EL = SMTH1(issuedPlts, 3)
issuedPlts = 9600-STEP(600, 5)+STEP(600, 6)
Order_delay = DELAY(DArrival_from_CT, Order_delay_time)
Order_delay_time = 1
{ The model has 75 (75) variables (array expansion in parens).
In 3 Modules with 0 Sectors.
Stocks: 15 (15) Flows: 15 (15) Converters: 45 (45)
Constants: 19 (19) Equations: 41 (41) Graphicals: 0 (0)
There are also 30 expanded macro variables.
}
```

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